District of North Vancouver

Debris Flow - Debris Flood Study and Risk Mitigation Alternatives for Deep Cove Creeks

Final Report
December 2003

District of North Vancouver

Debris Flow - Debris Flood Study and Risk Mitigation Alternatives for Deep Cove Creeks

Final Report
December 2003

KWL File No. 31.290

KERR WOOD LEIDAL
associates limited
CONSULTING ENGINEERS

STATEMENT OF LIMITATIONS

This document has been prepared by Kerr Wood Leidal Associates Ltd. (KWL) for the exclusive use and benefit of the District of North Vancouver. No other party is entitled to rely on any of the conclusions, data, opinions, or any other information contained in this document.

This document represents KWL's best professional judgement based on the information available at the time of its completion and as appropriate for the project scope of work. Services performed in developing the content of this document have been conducted in a manner consistent with that level and skill ordinarily exercised by members of the engineering profession currently practising under similar conditions. No warranty, expressed or implied, is made.

CONTENTS

FIGURES

TABLES

APPENDICES

Executive Summary

KERR WOOD LEIDAL
associates limited
CONSULTING ENGINEERS

EXECUTIVE SUMMARY

An Overview Report on Debris Flow Hazards was completed for the District of North Vancouver in April 1999 to identify the potential debris flow and debris flood hazards associated with the many creeks in the District. Following submission of the Overview Report, detailed debris flow and debris flood studies were initiated on several high risk creeks, including the Deep Cove creeks that are the subject of this report. The Deep Cove creeks include Panorama Creek, Mathews Creek, Gavles Creek, Cove Creek, Cleopatra Creek, Martin Creek and Francis Creek. The risks at these creeks are due to a debris flow or debris flood hazard and the presence of dense development along Panorama Drive.

The study concludes that the Deep Cove creeks are typically subject to periodic debris floods. The estimated debris flood magnitudes for design purposes (a 500-year return period) are a volume ranging from 100 m^3 to 250 m^3 with a peak discharge ranging from 3 m^3/s to 10 m^3/s. Exceptions are Martin Creek and Francis Creek which can produce debris flows at the 500-year return period. The estimated design debris flow magnitude on Francis Creek is a volume of 1,000 m^3 and a peak discharge of 25 m^3/s. Debris flows on Francis Creek can also overflow into Martin Creek, therefore Martin Creek is considered subject to debris flows of about the same magnitude as Francis Creek. Without mitigation structures, debris floods and debris flows on the study creeks could cause damage to houses, road crossings and other infrastructure.

The existing level of risk is rated medium high for Panorama Creek, Mathews Creek, Gavles Creek, Cove Creek and Cleopatra Creek, high for Francis Creek, and medium for Martin Creek. The target level of risk is moderately low, and mitigative measures would be required at the Deep Cove creeks to achieve this level.

A wide range of mitigative alternatives have been considered, including land use planning, watershed actions, debris flow mitigation structures (debris basin, debris barrier, channelization and deflection berms), and creek management measures.

At Francis Creek, risk mitigation would likely involve construction of a deflection berm (to prevent an avulsion into Martin Creek), a second smaller deflection berm to protect a house, a 2,000 m^3 debris basin above Indian River Drive, upgrading of the Indian River Drive culvert, and downstream channel works at the Deep Cove Marina. The combined cost of the works at Francis Creek would be about $1.4 million.

With the Francis Creek deflection berm, no migitative measures would be needed at Martin Creek. Mitigation of the risk at Panorama Creek, Mathews Creek, Gavles Creek, Cove Creek and Cleopatra Creek would involve debris barriers above the Panorama Drive development, along with various channel works. The cost of the mitigative works at these creeks would range from $300,000 to $500,000 per creek.

The combined cost of hazard mitigation for all the Deep Cove creeks would be roughly $3.1 million.

Section 1

Introduction

KERR WOOD LEIDAL
associates limited
CONSULTING ENGINEERS

1. INTRODUCTION

1.1 PURPOSE OF REPORT

This report provides a comprehensive assessment of the hazard posed by debris flows and debris floods on the Deep Cove creeks at Panorama Drive. The need for mitigative measures is also assessed, and a range of mitigative alternatives is reviewed. Supporting information is provided for alternatives considered feasible. This provides a basis for a decision by the District of North Vancouver on the possible implementation of mitigative measures.

1.2 BACKGROUND

UPPER MACKAY CREEK DEBRIS FLOW

A significant debris flow occurred in the District on Upper Mackay Creek on November 23, 1995, causing damage to homes and infrastructure. Prior to this event, there had been no documented debris flow occurrence in the developed parts of the District.

The District responded to the November 23, 1995 debris flow at Upper Mackay Creek by restoring the creek channel and commissioning a detailed study by KWL. The study proposed a mitigative strategy that was subsequently approved by Council and implemented. The mitigative scheme that is now in place includes a 13,000 m^3 debris basin to contain debris flows above the development area, as well as downstream channel improvements.

OVERVIEW STUDY OF DEBRIS FLOW HAZARDS

Following mitigation of the debris flow risk at Upper Mackay Creek, the District commissioned an overview study of debris flow hazards in other parts of the District. This culminated in publication of the *Overview Report on Debris Flow Hazards* in April 1999 by KWL and EBA. The Overview Report provided a preliminary assessment of debris flow hazard, consequence and risk for each creek. On this basis, eight creeks were identified as having ‘very high’ risk, and five creeks were given a ‘high’ risk rating. A general set of risk mitigation measures was provided for each creek studied.

Following completion of the Overview Report, funding was subsequently approved to perform detailed debris flow studies on the highest risk creeks, including the Deep Cove creeks, which are the focus of this report. The Deep Cove creeks consist of Panorama Creek, Mathews Creek, Gavles Creek, Cove Creek, Cleopatra Creek and Francis Creek. An additional high risk creek, Martin Creek, was identified during the course of the study. The risk at these creeks is a result of a significant debris flow or debris flood hazard, coupled with dense development along Panorama Drive.

1.3 DEBRIS FLOW AND DEBRIS FLOOD HAZARDS

Steep mountain creeks may be subject to geomorphic processes beyond pure water floods. Sediment and debris from watershed instability may provide the impetus for debris flows or debris floods. For the purposes of this report, these events are generally defined as follows:

- Debris Flow - A form of channelized landslide that usually occurs during a wet weather period on a steep mountain creek with abundant debris sources. Debris flows can reach up to 50 times the peak discharge of a 200-year return period flood.

- Debris Flood – A flood that carries an unusually high amount of sediment and/or debris, but not to the extent that the event character is transformed from a flood to a landslide. Debris floods can exceed five times the peak discharge of a 200-year return period flood.

Appendix A provides further background information on debris flows and debris floods.

Debris flow hazards in B.C. came into prominence in the early 1980s. Between 1981 and 1983, a total of eight debris flow events were recorded on the Squamish Highway creeks between Horseshoe Bay and Britannia Beach (Thurber, 1983), resulting in a total of 12 casualties. It is estimated that at least 135 people have died as a consequence of debris flows and debris floods in B.C. in the last century.

Debris floods may be visualized as an extension of the flood process, whereas debris flows behave very differently than floods. Therefore, mitigation of debris flow hazards requires a considerably different approach.

1.4 WORK PROGRAM

DEFINITION OF STUDY AREA

The study area comprises the watersheds of the Deep Cove creeks. The study area location is illustrated by Figure 1-1. Figure 1-2 is a photo mosaic of the Deep Cove creeks, while a detailed map of the lower reaches is included as Figure 1-3. Also included is Figure 1-4, which shows property ownership below Mount Seymour Provincial Park (based on information from the District's GIS system). The Deep Cove creeks are also sometimes referred to as the Panorama Drainage System, although Francis Creek is part of the Woodlands Drainage System located to the immediate east.

Fans on the Deep Cove creeks are poorly defined. This is due to extensive housing development and property landscaping along Panorama Drive, and the fact that most creeks have small sediment loads that do not promote the formation of clearly defined fans. For the purpose of this report, creek sections that flow through the developed area around Panorama Drive are termed fan reaches.

OBJECTIVES

The work program for this study was developed on the basis of the following objectives:

- quantify the debris flow, debris flood and flood hazards;
- identify risk mitigation alternatives; and
- provide recommendations regarding possible future mitigative actions.

With this information, the District can then consider implementation of mitigative measures.

WORK PROGRAM

The work program is summarized in Table 1-1.

Table 1: Work Program for Deep Cove Creeks

Major Activity	Work Tasks
1. Air Photo Interpretation	▪ Review available air photographs and note changes in the watershed, the creek channel and on the fan. ▪ Identify unstable terrain.
2. Watershed Mapping	▪ Create a 1:5000 scale map at a 5 m contour interval of the watershed showing main features (i.e. debris flow initiation areas, rockslides, developments, infrastructure, etc.). ▪ Create a 1:1000 scale topographic map (1 m contour interval) of the Panorama Drive area showing infrastructure, houses, and creek channels.
3. Field Reconnaissance	▪ Traverse accessible creek channel reaches. ▪ Obtain samples for dendrochronology (if possible), evaluate and quantify potential landslide dam outbreak scenarios, measure cross-sections at key locations. ▪ Quantify material stored in the channel of the Deep Cove creeks. ▪ Inspect Mount Seymour Road, Indian River Drive and Panorama Drive for drainage issues.
4. Debris Flow and Debris Flood Analysis	▪ Analyse field data and determine the frequency and magnitude of past debris flows and debris floods at the Deep Cove creeks. ▪ Determine debris flow and debris flood frequency/magnitude relations and establish design events (volume and peak discharge).
5. Risk Analysis	▪ Document infrastructure on the creek fan and complete an inventory of creek works on Deep Cove creeks.

Major Activity	Work Tasks
	▪ Rate risk on basis of hazard and consequence. ▪ Identify risk reduction on the basis of the target risk level.
6. Mitigative Alternatives	▪ Determine the need for mitigative measures and consider mitigative alternatives. ▪ Review and assess the feasibility of mitigative alternatives.
7. Draft Report	▪ Prepare a draft report. ▪ Include maps, drawings, and documentation of work tasks. ▪ Provide phasing plan for implementation where appropriate. ▪ Identify watershed management recommendations where appropriate.
8. Report Review	▪ Obtain in-house review of the draft report. ▪ Obtain District review of the draft report. ▪ Finalize the report on basis of review comments.

REPORT FORMAT

This report includes technical appendices that document specific parts of the investigation program (background information on debris flows and debris floods, photographs, watershed description, hydrologic analysis, debris flow and debris flood probability and magnitude assessment). Inclusion of most of the detailed technical content in the appendices allows the main report body to focus more closely on assessment and mitigation of debris flow and debris flood risks.

1.5 PROJECT TEAM

This report was written by Matthias Jakob, Ph.D., P.Geo., Hamish Weatherly, M.Sc., P.Geo., and Mike V. Currie, M.Eng., P.Eng., of Kerr Wood Leidal Associates (KWL). Nigel Skermer, M.Sc., P.Eng., also of KWL, was the Geotechnical Engineer. Input on behalf of the District of North Vancouver was provided by Len Jensen, A.Sc.T.

Section 2

Risk Analysis

2. RISK ANALYSIS

2.1 INTRODUCTION

This section provides a risk analysis for debris flow, debris flood and flood hazards on the Deep Cove creeks. This includes:

- analysis of debris flow, debris flood and flood *hazards*;
- assessment of the potential *consequences*; and
- establishment of *risk* and the need to implement mitigative measures.

The primary purpose of this section is to identify the risk management issues that are important to the District in considering possible implementation of mitigative measures. The overall risk is defined as the combination of hazard and consequence, where:

- *hazard* represents the occurrence of creek events, expressed in terms of probability and magnitude; and

- *consequence* represents the elements at risk and their vulnerability to damage during an event.

The level of risk, and therefore the need to consider implementation of mitigative measures, depends on both the degree of hazard and the potential consequences.

For general reference, Appendix B includes selected photographs of the study area and Appendix C provides a detailed physical description of the watersheds. Figure 2-1 is a geomorphic map of the watersheds, which is cross-referenced throughout this report.

2.2 PREVIOUS WORK

The Deep Cove creeks have been previously studied with regard to drainage and flooding:

1982 COMPREHENSIVE DRAINAGE STUDY

In 1982, KWL completed a comprehensive study of major and minor creek systems within the District of North Vancouver. The study provided the basis for implementation of a creek stabilization/upgrading program. The study findings consisted of 13 “working papers” covering specific areas of study. The July 1982 *Report on Deep Cove – Dollarton Area* dealt mainly with existing drainage facilities in the Deep Cove residential area, particularly along Panorama Drive. A program was subsequently implemented in 1983 to resolve site-specific problems, the majority of which were related to poor entrance conditions at culverts.

The report also identified the need for a comprehensive study on the impact of future large-scale residential development along Indian River Drive on the downstream Deep Cove creeks.

PANORAMA DRIVE CULVERT UPGRADING PROGRAM

The inlets for the Gavles Creek and Cove Creek culverts were reconstructed in 1990 as part of a culvert upgrading program. The culvert for Cleopatra Creek was replaced in 1991.

OVERVIEW ASSESSMENT OF MOUNTAINSIDE DRAINAGE ABOVE DEEP COVE

A draft report was issued by KWL in 1990 and focused on the Panorama drainage system. It was carried out to assess the hydrological impact of potential development on the Indian River Drive benchlands.

For this study, the 100-year return period peak flows were estimated for the existing conditions as well as an "after future development" scenario. In addition, the capacities of culverts were checked. The main findings of the 1990 report are:

- Gavles Creek has an unstable channel and requires attention.
- The proposed development of the Indian River Drive benchlands would result in increases in peak runoff rates between 15 and 25%.
- The upgraded culverts along Panorama Drive are generally adequate to convey present and future (after development) flood runoff. The only culvert remaining to be replaced and upsized is the Cleopatra Creek crossing.
- The Mathews Creek culvert along Panorama Drive requires minor wingwall improvements to provide a more effective transition from the natural channel to the intake structure.

The following table summarizes the 100-year return period peak flows at the significant creeks along Panorama Drive as estimated in the 1990 report.

Return Period (years)	**Panorama Creek** (m^3/s)	**Mathews Creek** (m^3/s)	**Gavles Creek** (m^3/s)	**Cove Creek** (m^3/s)	**Cleopatra Creek** (m^3/s)
100	3.0	2.3	2.1	2.4	1.7

REPORT ON NOVEMBER 23, 1995 FLOOD EVENT

On November 23, 1995, a rainstorm resulted in high flow conditions on all creeks and rivers in the District including the Deep Cove area. A KWL report was issued on November 28 that summarized the effects of the storm. Damage in the Deep Cove area is noted below.

A 900 mm culvert on Panorama Creek along lower Mount Seymour Road became blocked during the storm. The creek overflowed in a southwesterly direction along the roadside ditch into the Gallant Creek system. Mount Seymour Road was severely scoured and undermined in sections. Initially, the flow from Panorama Creek overflowed almost entirely to the Gallant Creek system, causing localized flooding along Gallant Avenue in Deep Cove. Culverts along Indian River Drive then became blocked or overwhelmed causing the road to be overtopped. Due to the blocked culverts along Indian River Drive, floodwaters further overflowed to the area between Panorama Creek and Gallant Creek. This secondary flow was conveyed into a small channel causing culverts to be surcharged and streets to be overtopped on Badger Road, Caledonia Avenue, and Panorama Drive.

Upstream of Panorama Creek, several culverts along the BC Hydro right-of-way and Old Buck Trail were plugged, causing several new creek channels to be formed. The plugging of culverts along Old Buck Trail may have diverted flows from Mathews Creek into Panorama Creek, causing increased debris transport and blockage of the culvert along Mount Seymour Road.

Immediate actions were carried out to clear the Panorama Creek culvert on Mount Seymour Road. Capilano Highway Services unplugged the culvert and it was subsequently replaced with a 1,200 mm diameter pipe on November 25. At Indian River Drive the 900 mm wood stave culvert on Panorama Creek was unplugged, and flow was restored into Gallant Creek. In Deep Cove, District staff excavated debris from culverts, sandbagged along streets, and removed debris from streets. The aftermath of this storm was a destabilized channel at Panorama Creek and Gallant Creek. There was probably more scour along sections of other creeks that were not visited because no specific problems were reported. The two Gallant Creek culverts on Indian River Drive were subsequently replaced.

The November 23, 1995 event clearly showed the danger of flood overflows from culvert blockages. Culvert sizing should therefore not only be carried out for water flow but should account for debris movement.

2.3 DEBRIS FLOW, DEBRIS FOOD AND FLOOD HAZARDS

This sub-section is a summary of Appendices D and E. It quantifies the hazards posed by debris flows, debris floods, and floods at the Deep Cove creeks. This represents an assessment of the watershed capability to produce these types of events, independently of the potential consequences of such events. Floods are dealt with first because flood magnitude has some bearing on the assessment of debris flood hazards.

DESIGN FLOOD EVENT

Design of mitigative works for flood hazards requires that the design flood event be quantified. In B.C., the 200-year return period flood is the accepted standard for flood protection measures. Appendix D provides an updated hydrologic analysis for the Deep Cove creeks, which is summarized as follows:

Return Period (years)	Panorama Creek (m^3/s)	Mathews Creek (m^3/s)	Gavles Creek (m^3/s)	Cove Creek (m^3/s)	Cleopatra Creek (m^3/s)	Martin Creek (m^3/s)	Francis Creek (m^3/s)
200	4.2	4.5	2.4	4.0	1.5	3.1	9.0

The field investigations have identified the potential for interflow between several of the Deep Cove creeks. In the upper watersheds, some tributary channels periodically shift from one watershed to another, resulting in increased flow in the receiving watershed. The above peak flow estimates provide reasonable allowances for such occurrences.

The above peak instantaneous flow estimates are considered adequate for the present purposes. Should it be necessary to take the estimates to a higher level of precision in the future, site-specific data for model calibration would be beneficial. This could be obtained by installation of a temporary hydrometric station in the vicinity of Indian River Drive.

There has been a general trend towards warmer and wetter conditions in coastal B.C. over the past 30 years, which is consistent with global climate change theory. Some allowance for this increasing trend has been made by rounding up the 200-year return period peak flow estimates.

In addition to the peak flow magnitude, it is necessary to consider the potential for flood flows to be accompanied by bedload and wood debris.

DEBRIS FLOW AND DEBRIS FLOOD PROBABILITY AND MAGNITUDE

Appendix E provides an analysis of the probability and magnitude of debris flows and debris floods on the Deep Cove creeks.

In general, a probability can be attached to the occurrence of debris flows or debris floods of a particular magnitude. This is a physical assessment of the hazard, independent of the consequences of such an event. In many situations, different debris flow or debris flood magnitudes may occur on a particular creek with varying probabilities. For example, small or medium size debris flows usually occur more frequently than larger ones. This is particularly true for creeks with multiple tributary branches, and large amounts of debris. The probability of events such as debris flows, debris floods, avalanches and landslides is often best assessed with extreme value distributions similar to those used in flood frequency analysis.

Frequency-magnitude relationships are largely controlled by the watershed type (i.e. the amount of sediment available for debris flow transport). Watersheds with a quasi-infinite amount of stored debris will respond more readily to triggering hydroclimatic events and show a very large range of possible debris flow and debris flood magnitudes. Watersheds with a limited amount of stored debris have to recharge after each significant event, and hence the event volume at any given time is more limited and more predictable. Other factors influencing the frequency/magnitude relationships of debris flows and debris floods are the severity of hydroclimatic events, the watershed morphometry, geotechnical characteristics of the source materials, and vegetation cover.

For the purposes of this report, Appendix E incorporates the following probability classifications for debris flows and debris floods:

Probability	Return Period	Probability of at Least One Occurrence in 50 Years[1]
Very High	less than 20 years	more than 90%
High	20 to 100 years	40% to 90%
Medium	100 to 500 years	10% to 40%
Low	more than 500 years	less than 10%

[1] Probabilities are rounded to the nearest 5%.

The return period is the average recurrence interval for a particular event magnitude. Greater return periods indicate less frequent (and larger magnitude) events. There is no very low probability class because there is no physical evidence available that warrants extrapolation to such low probabilities. The probability of occurrence noted in the above table provides a more easily interpretable measure of hazard probability.

All the above factors have to be considered in assessing debris flow or debris flood frequency-magnitude relationships and determining the design events.

For development of debris flow or debris flood mitigation measures, a *design debris flow event* is often selected. While there is no legislated design debris flow standard in B.C., there is increasing consensus that this should be based on the 500-year return period (10% in 50 years probability of occurrence), which correlates to the upper level of the medium probability event. This criterion is used as a geotechnical design parameter for seismic design in the B.C. Building Code and for some slope stability analyses.

DESIGN DEBRIS FLOOD AND DEBRIS FLOW MAGNITUDES FOR DEEP COVE CREEKS

Most of the Deep Cove creeks have been identified as prone to debris floods, however Francis Creek and Martin Creek are susceptible to debris flows within the design event return period of 500 years. Most of the creeks are not considered susceptible to debris flows at the very high, high and medium probabilities because of:

- the lack of steep channel gradients;
- the lack of debris flow deposits along the channels or within the fan areas;
- the lack of high impact marks on trees along the channels; and
- the potential sideslope failures are considered too small to trigger debris flows.

However, a debris flow could result from a large sideslope failure during an extreme hydroclimatic event. Although this is a very remote possibility it cannot be fully discarded and is considered possible in the low probability scenario.

In contrast, debris floods are likely to occur on most of the creeks. Debris flood magnitude on steep mountain creeks may be estimated reliably if there is geomorphic or botanical evidence that allows the reconstruction of peak discharge. Otherwise, magnitude may be assessed empirically using judgement and experience. Because of a lack of suitable geomorphic or botanical evidence, the latter approach is used for this study.

Francis Creek, though it shows no obvious signs of past debris flow activity, is believed to have the capability of producing debris flows because of steep headwater slopes, a steep gradient, high discharge and sediment wedges of significant size. Martin Creek, despite its small drainage area, is also considered subject to debris flows due to a potential avulsion from Francis Creek.

On the basis of Appendix E, the following is a summary of estimated debris flow and debris flood magnitudes for various probability classifications on Panorama Creek, Mathews Creek, Gavles Creek, Cove Creek, Cleopatra Creek, Martin Creek and Francis Creek.

Panorama Creek

Probability	Probability of Occurrence in 50 Years	Volume (m^3)	Peak Discharge (m^3/s)	Geomorphic Process
Very High	more than 90%	5	3	Flood
High	40% to 90%	20	6	Debris Flood
Medium	**10% to 40%**	**200**	**10**	**Debris Flood**
Low	less than 10%	600	16	Debris Flow
The event magnitudes are estimated for the upper limit of development along Panorama Drive.				

Based on the above data and the medium probability criterion, a volume of 200 m^3 is selected as the design debris flood event for Panorama Creek. The corresponding peak discharge at Panorama Drive is 10 m^3/s.

Mathews Creek

Probability	Probability of Occurrence in 50 Years	Volume (m^3)	Peak Discharge (m^3/s)	Geomorphic Process
Very High	more than 90%	5	3	Flood
High	40% to 90%	15	5	Debris Flood
Medium	**10% to 40%**	**150**	**9**	**Debris Flood**
Low	less than 10%	500	13	Debris Flow
The event magnitudes are estimated for the upper limit of development along Panorama Drive.				

Based on the above data and the medium probability criterion, a volume of 150 m^3 is selected as the design debris flood for Mathews Creek. The corresponding peak discharge at Panorama Drive is 9 m^3/s.

Gavles Creek

Probability	Probability of Occurrence in 50 Years	Volume (m^3)	Peak Discharge (m^3/s)	Geomorphic Process
Very High	more than 90%	5	2	Flood
High	40% to 90%	20	4	Debris Flood
Medium	**10% to 40%**	**250**	**8**	**Debris Flood**
Low	less than 10%	800	20	Debris Flow
The event magnitudes are estimated for the upper limit of development along Panorama Drive.				

Based on the above data and the medium probability criterion, a volume of 250 m^3 is selected as the design debris flood for Gavles Creek. The corresponding peak discharge at Panorama Drive is 8 m^3/s.

Cove Creek

Probability	Probability of Occurrence in 50 Years	Volume (m^3)	Peak Discharge (m^3/s)	Geomorphic Process
Very High	more than 90%	5	3	Debris Flood
High	40% to 90%	20	6	Debris Flood
Medium	**10% to 40%**	**250**	**10**	**Debris Flood**
Low	less than 10%	800	20	Debris Flow
The event magnitudes are estimated for the upper limit of development along Panorama Drive.				

Based on the above data and the medium probability criterion, a volume of 250 m^3 is selected as the design debris flood for Cove Creek. The corresponding peak discharge at Panorama Drive is 10 m^3/s.

Cleopatra Creek

Probability	Probability of Occurrence in 50 Years	Volume (m^3)	Peak Discharge (m^3/s)	Geomorphic Process
Very High	more than 90%	2	1	Flood
High	40% to 90%	10	2	Debris Flood
Medium	**10% to 40%**	**100**	**4**	**Debris Flood**
Low	less than 10%	400	11	Debris Flow
The event magnitudes are estimated for the upper limit of development along Panorama Drive.				

Based on the above data and the medium probability criterion, a volume of 100 m^3 is selected as the design debris flood for Cleopatra Creek. The corresponding peak discharge at Panorama Drive is 4 m^3/s.

Martin Creek

Probability	Probability of Occurrence in 50 Years	Volume (m^3)	Peak Discharge (m^3/s)	Geomorphic Process
Very High	more than 90%	2	1	Flood
High	40% to 90%	10	2	Debris Flood
Medium	**10% to 40%**	**1,000**	**25**	**Debris Flow**
Low	less than 10%	1,500	35	Debris Flow
The event magnitudes are estimated for the crossing of Indian River Drive.				

Martin Creek is unique to the study area as an avulsion from Francis Creek could reach the Martin Creek drainage as detailed in Appendix E. Based on the above data and the medium probability criterion, a volume of 1,000 m^3 is selected as the design debris flow event for Martin Creek. The corresponding peak discharge at Indian River Drive is 25 m^3/s.

Francis Creek

Probability	Probability of Occurrence in 50 Years	Volume (m^3)	Peak Discharge (m^3/s)	Geomorphic Process
Very High	more than 90%	several 10s	5	Debris Flood
High	40% to 90%	several 100s	10	Debris Flood
Medium	**10% to 40%**	**1,000**	**25**	**Debris Flow**
Low	less than 10%	2,000	45	Debris Flow
The event magnitudes are estimated for the upstream end of the box culvert at Deep Cove Marina.				

Based on the above data and the medium probability criterion, a volume of 1,000 m^3 is selected as the design debris flow event for Francis Creek. The corresponding peak discharge at the fan apex is 25 m^3/s.

SUMMARY OF DESIGN DEBRIS FLOODS AND DEBRIS FLOWS

The design debris flow and debris flood estimates for the Deep Cove creeks are summarized as follows:

Creek Name	Debris Flood Volume (m^3)	Debris Flood Peak Discharge (m^3/s)	Debris Flow Volume (m^3)	Debris Flow Peak Discharge (m^3/s)
Panorama Creek	200	10	N/A	N/A
Mathews Creek	150	9	N/A	N/A
Gavles Creek	250	8	N/A	N/A
Cove Creek	250	10	N/A	N/A
Cleopatra Creek	100	4	N/A	N/A
Martin Creek	N/A	N/A	1,000	25
Francis Creek	N/A	N/A	1,000	25

The above estimates are based on current understanding of debris flow and debris flood systems and analytical techniques. The estimates in this report are, therefore, based on judgement in view of comparable studies in southwestern B.C.

Notwithstanding selection of the design events, it is still prudent to consider the full range of potential event magnitudes for events greater than the 500-year probability in the overall risk mitigation strategy. This is addressed later in this section.

2.4 POTENTIAL CONSEQUENCE

This sub-section provides an assessment of the potential consequences of debris flows and debris floods on the Deep Cove creeks. Understanding these impacts is important as they determine the risk that forms the basis for consideration of mitigative works.

CONSEQUENCE RATING SYSTEM

The overall potential consequence of a debris flow or debris flood can be rated as follows:

Consequence	Description
Very High	Direct debris impact with extensive structural damage.
High	Direct or indirect debris impact with some potential for structural damage along with significant sediment deposition and flooding.
Medium	Indirect debris impact. No structural damage but damage to houses and property from sediment deposition and flooding.
Low	Sediment deposition and flooding with minor property damage only.
Very Low	Virtually no damage.

While this rating system focuses on structural and property damage, the potential for injury and loss of life should also be considered. In general, this decreases in accordance with the consequence rating.

STRUCTURES IN UPPER WATERSHEDS

Any structure constructed on a steep slope or along the creek corridor may be subject to impacts resulting from a spectrum of creek processes, ranging from floods to debris flows.

Mount Seymour Road, Indian River Drive and several trail crossings (Baden-Powell Trail etc.) are within the watersheds of the Deep Cove creeks. More than representing assets at risk, the drainage works associated with the roads may divert flow from one tributary channel to another, or even between watersheds. In the event of Indian River Drive being closed due to creek-related problems, road access to the Indian Arm areas of the District would be cut off.

CREEK EVENT IMPACTS AT PANORAMA CREEK, MATTHEWS CREEK, GAVLES CREEK, COVE CREEK AND CLEOPATRA CREEK

The fan reaches may be subject to significant scour and erosion during a large flood where they are not stabilized by channel bottom stabilizers, culverts, concrete walls and other structures. For most of the creeks, this is likely to occur at the upstream end of the fan reaches due to the typical presence of instream engineering works downstream. Flood overflows are most likely to occur as a result of blockages at poorly confined locations, and these could result in flood and erosion damage to buildings on the fan reaches.

The design events for the creeks could potentially result in direct impact at several of the residential buildings along the fan reaches. The potential for damage is variable, depending on location (vicinity to the present channel), topography, culvert blockage, and building elevation with respect to surrounding grade. In general, however, houses immediately downslope of the fan apexes (i.e. above Panorama Drive) have the greatest potential for damage. The potential for damage to specific houses during a flood or debris flood is summarized below:

Panorama Creek: Sufficient channel capacity is available for the design debris flood at Panorama Creek to flow under the house addition for #2525 (Photo P-4). However, channel avulsion is possible at the fan apex and a debris flood could impact the back of the house. The house to the right (west) is located on high ground above the creek channel. At Panorama Drive, the culvert and channel have sufficient capacity for the 200-year return period flood in the absence of blockages or significant debris movement. The culvert inlet is well constructed with a headwall and wingwalls that provide a smooth transition for peak flows.

Mathews Creek: Like Panorama Creek, Mathews Creek is poorly confined at the fan apex. As such, a debris flood could directly impact the back of house #2603 (Photo M-4). A debris flood could also avulse to the right of the channel and flow down a driveway onto Panorama Drive. The channel has sufficient capacity to contain flood flows up to the 200-year return period flood level in the absence of blockages or significant debris movement. At Panorama Drive, the culvert has sufficient capacity for the 200-year return period flood in the absence of blockages.

Gavles Creek: Upstream of Panorama Drive, Gavles Creek flows adjacent to two properties. At the upstream limit of development, the creek emerges from confinement to flow parallel to house #2681 (Photo G-4). A further 30 m downstream the creek flows through property #2679. Here the creek flows under a wooden deck for about 10 m before emerging into an engineered channel on the west side of the property. Channel avulsions are likely at both houses due to limited cross-sectional area. The design debris flood would result in direct debris impact to both residences. Gavles Creek has insufficient capacity for the 200-year return period flood where the channel flows under the wooden deck, although detailed measurements were restricted as the site is on private property (cross-section area approximately 1 m^2). At Panorama Drive, the culvert has marginal capacity for the 200-year return period flood.

Cove Creek**:** Downstream of the fan apex, Cove Creek flows in a southeasterly direction skirting the backyards of several properties (Photo C-3). Avulsions appear unlikely through this section, as the cross-sectional area is about 10 m^2. Before reaching Panorama Drive, however, the creek flows under house #2735 (Photo C-4). At this location, a 1.5 m wide concrete channel with stone walls has been constructed under the house. The design debris flood could result in direct impact to exposed structures that support the house. Where the channel flows under the house, there also appears to be insufficient capacity for the 200-year return period flood. At Panorama Drive, the culvert has sufficient capacity for the 200-year return period flood in the absence of blockages. The culvert inlet is well constructed with a rock headwall and wingwalls that provide a smooth transition for peak flows.

Cleopatra Creek: At the fan apex, Cleopatra Creek flows into the back yard of house #2755 (Photo CL-2). While the main part of the house is not likely to be damaged by the design debris flood, the creek does flow to the immediate east of the house. Here the creek flows under a workshop and through a 1,000 mm culvert, above which a patio has been constructed (Photo CL-3). Both structures could be directly impacted by a debris flood. Where the channel flows under the workshop, a channel avulsion could also occur during a 200-year return period flood. Unlike the other creeks along Panorama Drive, the culvert for Cleopatra Creek is poorly constructed, with a vertical drop to the inlet and a lack of wingwalls. However, the culvert does have sufficient capacity for the 200-year return period flood in the absence of blockages.

In addition to the potential for direct or indirect debris impact during a design debris flood, all of the above houses are subject to property damage from sediment deposition and flooding. During the design events, debris is unlikely to be transported across Panorama Drive to directly affect houses further downslope. However, the culverts are likely to become plugged with debris. As a result, the road grade could be damaged, cutting off access to some of the houses and the Deep Cove Marina. Damage to watermains and other utilities may also occur. In addition, flood damage would likely occur at houses located along the creek corridor and below the road.

The total assessed value of all properties along the fan reaches is in the tens of millions of dollars.

The potential consequences described above are for the upper end of the medium probability event (500-year return period). At the lower end of this probability class (100-year return period), the potential damages would be less severe. For a high probability debris flood (20 to 100-year return period), the potential peak discharge is similar to the 200-year return period flood. While all of the creeks have sufficient capacity for such flows, sedimentation associated with a high probability debris flood could cause an avulsion and result in flooding damage to property and/or houses.

CREEK EVENT IMPACTS AT FRANCIS CREEK AND MARTIN CREEK

The Francis Creek channel generally has sufficient capacity to contain flood flows up to the 200-year return period flood level in the absence of blockages or significant debris movement. However, the box culvert under the Deep Cove Marina is slightly undersized for the peak flow estimate of 8.6 m^3/s. Under surcharged conditions, the culvert has a maximum capacity of about 6 m^3/s. Overflows would flow across the parking lot and possibly flood buildings.

The design debris flow could result in direct impact to the buildings at the Deep Cove Marina. In addition, the parking lot and box culvert could sustain damage (Photo F-11). A debris flow could also result in indirect debris impact to a house located along the creek corridor approximately 200 m above Indian River Drive (Photo F-6). The 1,500 mm culvert at Indian River Drive would be damaged by the design debris flow and the road bed could sustain significant damage.

For a high probability event (20-year to 100-year return period), debris flows are not expected to occur. At the upper end of this probability class, however, a debris flood is estimated to have a peak discharge of 10 m^3/s. A peak flow of this magnitude could overwhelm the box culvert at the marina and possibly flood buildings.

A design debris flow on Francis Creek could avulse up to 1,000 m^3 of debris into the Martin Creek watershed. A debris flow of this magnitude would be transported down a well vegetated gully toward Indian River Drive. Here the creek flows through a 600 mm wooden culvert. Both the culvert and road surface would be damaged by the design event. For downstream reaches, it is difficult to estimate the potential damage as the channel is well vegetated and a significant portion of the debris flow could remain in storage at the crossing. While the channel of Martin Creek has sufficient capacity for the 200-year return period flood at Panorama Drive, flood flows associated with the design debris flow could overwhelm the channel and culvert, and thereby cause property damage to house #2833 and other residences.

2.5 POTENTIAL DEBRIS FLOW AND DEBRIS FLOOD RISKS

DEFINITION AND CLASSIFICATION OF RISK

Debris flow, debris flood and flood risk can be defined as the combination of hazard (event probability and magnitude) and consequence (vulnerability to damage). Assessment of both hazard and consequence, and therefore risk, can be performed qualitatively on the basis of analysis and judgement. For this study, hazard probability is defined on the basis of Appendix E and Section 2.2. Consequence is rated according to the rating table in Section 2.3.

Qualitatively, risk can be assessed for a fan area by using the following matrix:

Hazard Probability	Consequence				
	Very High	**High**	**Medium**	**Low**	**Very Low**
Very High	Very High	Very High	High	Medium High	Medium Low
High	Very High	High	Medium High	Medium	Low
Medium	High	Medium High	Medium	Medium Low	Low
Low	Medium	Medium	Medium Low	Low	Very Low
The shading symbolizes acceptable risk levels.					

A risk analysis is presented for the Deep Cove creeks in the following sub-section. In the absence of any established standard for risk acceptability in B.C., for the purposes of this report, a medium low or lower level of risk has been adopted as the target level of residual risk following the implementation of mitigative measures. This is subject to review in the future if the District adopts a policy in this respect.

EXISTING AND TARGET LEVEL OF RISK AT DEEP COVE CREEKS

Panorama, Mathews, Gavles, Cove, and Cleopatra creeks share identical risk matrices. The existing level of risk at these creeks for various debris flow, debris flood, and flood hazard scenarios is contrasted with the target levels as follows:

Hazard Probability	Process	Existing Conditions		Target Level	
		Consequence	**Risk**	**Consequence**	**Risk**
Very High	Flood	Very Low	Med. Low	Very Low	Med. Low
High	Debris Flood	Medium	Med. High	Very Low	Low
Medium	**Debris Flood**	**High**	**Med. High**	**Low**	**Med. Low**
Low	Debris Flow	Very High	Medium	Medium	Med. Low

The above table illustrates that under existing conditions, medium probability debris floods at the above Deep Cove creeks pose a medium high risk. The implication is that events having return periods of 100 to 500 years (10% to 40% chance in 50 years) will cause direct or indirect impact damage. The target level of risk (the residual risk after mitigative measures) is medium low, and this dictates reducing the debris flood consequences to low.

The above table indicates that mitigative measures should be considered with the following objectives:

- for a low probability event (debris flow), reduce the potential consequence to medium (no structural damage);

- for a medium probability event (debris flood), reduce the potential consequence to low (property damage only); and

- for a high probability debris flood, reduce the potential consequence to very low (virtually no damage).

This approach will be followed up in Section 3 where specific mitigative strategies are considered.

The risk matrix for **Martin Creek** is as follows:

Hazard Probability	**Process**	**Existing Conditions**		**Target Level**	
		Consequence	**Risk**	**Consequence**	**Risk**
Very High	Flood	Very Low	Med. Low	Very Low	Med. Low
High	Flood	Very Low	Low	Very Low	Low
Medium	**Debris Flow**	**Medium**	**Medium**	**Low**	**Med. Low**
Low	Debris Flow	High	Med. High	Medium	Med. Low

The above table illustrates that under existing conditions, medium probability debris flows at Martin Creek pose a medium risk (bold row). The implication is that events having return periods of 100 to 500 years (10% to 40% chance in 50 years) will cause indirect debris impact. The target level of risk (the residual risk after mitigative measures) is medium low, and this dictates reducing the debris flow consequences to low (property damage only).

The above table indicates that mitigative measures should be considered for the following objectives:

- for a low probability event (1,500 m^3 debris flow), reduce the potential consequence to medium (no structural damage); and

- for a medium probability event (1,000 m^3 debris flow), reduce the potential consequence to low (property damage only).

This approach will be followed up in Section 3 where specific mitigative strategies are considered.

The risk matrix for **Francis Creek**, is as follows:

Hazard Probability	Process	Existing Conditions		Target Level	
		Consequence	Risk	Consequence	Risk
Very High	Debris Flood	Very Low	Med. Low	Very Low	Medium
High	Debris Flood	Low	Medium	Very Low	Low
Medium	**Debris Flow**	**Very High**	**High**	**Low**	**Med. Low**
Low	Debris Flow	Very High	Medium	Medium	Med. Low

The above table illustrates that under existing conditions, medium probability debris flows at Francis Creek pose a high risk (bold row). The implication is that events having return periods of 100 to 500 years (10% to 40% chance in 50 years) will cause direct impact damage. The target level of risk (the residual risk after mitigative measures) is medium low, and this dictates reducing the debris flow consequences to low (property damage only).

The above table indicates that mitigative measures should be considered for the following objectives:

- for a low probability event (2,000 m^3 debris flow), reduce the potential consequence to medium (no structural damage);
- for a medium probability event (1,000 m^3 debris flow), reduce the potential consequence to low (property damage only); and
- for a high probability debris flood, reduce the potential consequence to very low (virtually no damage).

This approach will be followed up in Section 3 where specific mitigative strategies are considered.

Section 3

Risk Mitigation Alternatives

KERR WOOD LEIDAL
associates limited
CONSULTING ENGINEERS

3. RISK MITIGATION ALTERNATIVES

3.1 INTRODUCTION

Section 2 documents creek-related hazards, defines the potential consequences of creek events, and describes the risks that arise from the combination of creek hazards and potential consequences. Based on these findings, this section reviews alternative strategies for risk mitigation at the Deep Cove creeks. For the purposes of considering possible applications, the focus is on events in the order of the design event magnitude as listed in Section 2.3.

There are two strategies for mitigating debris flow and debris flood hazards:

- active measures to mitigate the hazard occurrence; or
- passive measures to avoid the hazard, such as land use planning.

Active measures are usually needed when a debris flow or debris flood affects a developed area. Passive measures can be used to preclude development in high hazard areas, or can complement active measures to maximize safety in high risk areas.

3.2 LAND USE PLANNING

Land use planning is the primary form of passive measure for natural hazard mitigation. In a case where a fan is already developed, such measures are generally limited in application, and are best considered for implementation in conjunction with active measures to minimize risks.

ZONING

In some cases, it is possible to delineate a fan into zones of varying hazards, either with or without mitigative measures. Because of dense development along Panorama Drive, there is minimal opportunity for zoning.

LAND ACQUISITION

Acquisition of some property along creek corridors may be beneficial for future mitigation structures, so development activity in this area should be closely scrutinized. In addition, the need for building setbacks, erosion protection works and floodproofing measures should be considered on a site-specific basis. Provision of maintenance access routes or easements along the creek should also be considered at such time.

DEVELOPMENT OF EXISTING LOTS

There are several undeveloped lots above the existing Panorama Drive development. Some of the lots are situated along creek corridors and could be subject to creek hazards. Development of these lots should only be considered following a detailed hazard assessment.

The nature of the creek hazards on the Deep Cove creeks is such that effective mitigation on a site-specific basis may be feasible in many situations. Any proposed development along the creeks would require a building permit application to the District, and it is understood that a building permit would only be issued if a satisfactory professional engineer's report were submitted pursuant to Section 699 of the Municipal Act (soon to be Community Charter). The engineer's report would need to address the need for mitigative measures, the possible transfer of risk to other properties, and the requirement for maintenance work.

If a comprehensive mitigative scheme were to be implemented, it would be possible to define compatible floodproofing measures for development of existing lots that are not subject to acquisition.

3.3 WARNING SYSTEMS

Systems can be installed to provide warning of an impending debris flow (advance warning system), a debris flow occurring (event warning system), or after a debris flow has occurred (post-event warning system). An event warning system is not warranted for the Deep Cove creeks given that the period of warning would be minutes at best. The other two types of warning systems are discussed below.

ADVANCE WARNING SYSTEMS

Advance warning systems can involve real-time monitoring of precipitation and creek flow data to determine when hydrological conditions approach a threshold for regional landslide occurrence and debris flow activity. Activities in high-risk areas may then be restricted and public notification considered. The period of notice may range from a few hours to a day or two. Warnings will typically apply to all creeks in a regional area as opposed to any specific creek. False warnings may occur relatively often. An advance warning system (in the form of a hydroclimatic threshold for landslide initiation) has recently been developed for use by the GVRD at Grouse Mountain.

An advance warning system would be most applicable to warn watershed users (i.e. hikers) of high risk periods. Watershed access could be discouraged, or even possibly disallowed, during such periods. An advance warning system could also warn downstream residents and road users of high risk periods. But given the high likelihood of false warnings, it would not provide an effective means for temporarily relocating residents.

POST-EVENT WARNING SYSTEMS

Post-event warning systems may be useful in providing notice of a service disruption of critical infrastructure, such as bridges. Such a system would have been effective in preventing multiple deaths in 1981 at M Creek on the Squamish Highway, resulting from several vehicles driving unknowingly into a gorge following a bridge washout (a similar situation occurred on Rutherford Creek near Pemberton in October 2003).

A post-event warning system could not readily be implemented at the Deep Cove creeks as culverts, not bridges, are at risk.

3.4 WATERSHED MANAGEMENT ACTIONS

This section describes some general and site-specific watershed actions that should be considered in mitigating the risks associated with debris flows and debris floods at Deep Cove.

WATERSHED STABILIZATION

Watershed stabilization activities can be considered to reduce the level of debris flow and debris flood hazard. Such measures attempt to tackle the problem at the source area where debris is generated and point source failures are most likely.

Mathew Creek, Cleopatra Creek and Martin Creek

At Mathews Creek, Cleopatra Creek and Martin Creek there are no obvious unstable areas along the channels. During peak flow events (particularly if water diverts from one watershed into another, channel scour could destabilize sideslopes and cause shallow debris slides. However, there are no specific sideslope areas that require stabilization.

Cove Creek, Gavles Creek and Panorama Creek

At Cove Creek, Gavles Creek, and Panorama Creek, there are several locations where sediment has been delivered to the creek channel by either creek bank erosion or small sideslope failures in glacial till. Over tens to hundreds of years, the sediment storage volume will increase and could release suddenly during a debris flood. Stabilization efforts in these creek gullies could involve bioengineering techniques for the sideslopes (not necessarily requiring road access). This action would not solely reduce the risk to an acceptable level, but would decrease sediment input to the creek channels.

Francis Creek

During an October 2001 site visit, potential slope instability was observed at the lower switchback of Mount Seymour Road that could impact Francis Creek. A fill slope failure at this location could dam Francis Creek and possibly initiate a debris flow. Mitigation of this potential problem could involve partial removal of fill material and/or stabilization at the toe of the fill where the creek runs past.

CHECK DAMS

Check dams are weirs, typically constructed of concrete, about 2 m to 3 m high that can be constructed in series along a creek channel. Their primary purpose is to reduce debris production along creek channels. This is accomplished by storing in-channel material, stabilizing sideslopes, and directing the creek flow toward the centre of the channel. Check dams are often used for this purpose in Europe.

Check dams on the Deep Cove creeks would intermittently store debris, decrease the local slope, and if well anchored into the sideslopes would reduce debris production. For aesthetic reasons, the check dams could be constructed of wood. The check dams would preferentially be located in channel sections where the bed material is composed of loose, erodible sediment.

Check dams will not significantly reduce the debris flood or debris flow risk. In addition, implementation would be costly due to difficult access. Figure 3-1 illustrates the possible construction of a cedar log check dam along an incised reach of Cleopatra Creek as an example.

Check dams are not considered to be a viable option for Francis Creek due to long bedrock sections and significantly greater channel length along which they would have to be constructed. They are also not a suitable option for Martin Creek, where the design event results from a channel avulsion of Francis Creek.

TRAIL CROSSINGS

Trails crossing the creek channels are potentially at risk of washout from floods, debris floods, and/or debris flows. For the study area, the main crossing is the Baden-Powell Trail, which intersects all of the creeks (except Francis Creek) between Panorama Drive and Indian River Drive (Figure 2-1). In all instances there are small wooden bridges crossing the creeks. The crossings do not disturb natural creek processes, but may become damaged in the event of a debris flood as the trail crosses the creeks in their gullied reaches. Above Indian River Drive, the creeks are again crossed by the Baden-Powell trail but the risk of creek damage is significantly lower in this area.

At Francis Creek, there is a trail crossing at 560 m elevation where the creek is spanned by a solid wooden footbridge. Because the creek is poorly confined at this location, it could easily avulse and flow around the footbridge and erode the trail.

Warning signs may be appropriate to alert hikers as to the potential hazards.

CULVERT CROSSINGS

Above Indian River Drive there is the potential for culverts on Mount Seymour Road to become blocked, resulting in overflow of floodwater and debris to an adjacent watershed. A recent example is the storm of November 23, 1995, during which a 900 mm culvert became blocked at Panorama Creek and overflowed into the Gallant Creek watershed, causing localized flooding along Gallant Avenue in Deep Cove.

Mount Seymour Road is a particular problem because it strikes diagonally across the watersheds. Hence, ditch flow enters the culverts from the up road direction only. In contrast, Indian River Drive runs perpendicular to the slope and ditch flow typically enters the culverts on both sides (i.e. Panorama Creek, Mathews Creek, Gavles Creek, Cove Creek, and Francis Creek). For the former scenario, a plugged culvert would result in water being diverted to the next culvert down the road. For the latter case, the diverted water would flow over the road, potentially damaging the road bed, but remaining within the drainage.

The flood overflow concern is greatest along the lowest switchback of Mount Seymour Road. The most likely overflow scenarios identified are Gavles Creek into Mathews Creek and Mathews Creek into Panorama Creek (Figure 2-1). For higher elevation road sections, there is less concern about overflows as less of the watershed area is drained by the respective culverts.

Risks associated with culvert blockage and/or overflow could be addressed by culvert upgrading programs. For Mount Seymour Road, it would be appropriate to estimate design peak flows for each culvert and develop a culvert upgrading plan. Where appropriate, culverts could be designed to incorporate some allowance for flood overflow.

Culvert inspections prior to and during storm events can also be helpful in identifying debris accumulations that pose blockage risks. Maintenance programs should ensure that culvert entrances remain unobstructed.

FLOOD AVULSION POINTS

In addition to culvert crossings, flood overflow is possible at several locations in the watersheds (the most probable locations are shown on Figure 2-1). Particular areas of concern are described as follows:

- Old Buck Trail between the two lower sections of Mount Seymour Road. The trail is a steep old logging road and flow from Mathews Creek could overflow into Panorama Creek, particularly as Mathews Creek is poorly confined at the culvert crossings.
- Cove Creek originates at an elevation of approximately 450 m. On review of the local topography, it appears that the watershed area extends further upslope

(Figure 2-1). However, an upstream tributary channel runs parallel to Mount Seymour Road and discharges into Francis Creek. A portion of flow in the tributary channel escapes south into the drainage of Cove Creek at an elevation of 480 m. Here the channel is poorly incised and avulsions are possible.

- At the Cove Creek crossing of Indian River Drive, an ephemeral channel is located to the west of the main channel. The ephemeral channel discharges at the watershed boundary and some of the ditch flow is directed into Cove Creek and some into Gavles Creek. While the ephemeral channel does not capture a significant portion of watershed flow, upstream avulsions could increase its flow during a peak event.

- Part of Panorama Creek could avulse into Kai Creek below Indian River Drive. This could result in flood damage at Panorama Drive.

Some watershed management measures that would reduce the potential for flood overflows are as follows:

- the culvert crossings on Old Buck Trail could be improved by upgrading the ditch blocks and creating swales on the road bed;

- a small berm could be constructed at the potential avulsion from the Francis Creek tributary into Cove Creek;

- a more pronounced ditch should be created along Indian River Drive to ensure all the ditch flow from the ephemeral channel flows into the main channel of Cove Creek; and

- additional trenching and/or berming could be undertaken to prevent Panorama Creek overflows to Kai Creek (some such work was performed in the 1990s).

INSPECTION

General creek inspections should be undertaken. The purpose would be to identify watershed and channel instability. This would necessitate ground inspections since the dense tree canopy makes helicopter inspection difficult.

3.5 DEBRIS FLOW AND DEBRIS FLOOD MITIGATION STRUCTURES

This sub-section reviews alternative mitigative structures that could be constructed to mitigate the debris flow and/or debris flood risk. This includes a review of possible options, and identification of alternatives that may be applicable to the Deep Cove creeks. Conceptual design drawings are provided for selected alternatives. Design concepts and cost estimates are to a preliminary level, intended solely for comparison among alternatives.

The review of structural options focuses on the design event magnitudes as identified in Section 2.3 (i.e. a debris flood of up to 250 m^3 on Panorama, Mathews, Gavles, Cove and Cleopatra Creeks, and a 1,000 m^3 debris flow on Francis Creek and Martin Creek).

DEBRIS BASINS

A debris basin is a constructed storage area in which a debris flow is contained above a critical area. A debris basin includes an outlet structure that can be designed to allow passage of debris below a certain size.

From Panorama Creek to Cleopatra Creek, debris basins could be constructed upstream of the developed areas along Panorama Drive. Based on the estimated volumes of the design events, the size of the debris basins would range from 100 to 250 m^3. Any debris basins constructed on these creeks would therefore be relatively small compared to the more active debris flow creeks in the District. As the size of debris basin would be relatively small, and since the design considerations would be much the same as for a debris barrier, this issue is discussed further under the debris barrier heading below.

There is not an adequate debris basin site along the lower reaches of Francis Creek below Indian River Drive. However, a debris basin could be built directly upstream of Indian River Drive for a design debris flow of 2,000 m^3 (or 1,000 m^3 if a flow deflection berm is not constructed at the potential avulsion route into Martin Creek). In comparison to the creeks further west, site access would not be a problem. The potential site for such a debris basin is shown on Figure 3-2. A debris basin of this magnitude would cost approximately $400,000.

DEBRIS BARRIERS

Traditional Debris Barriers

A debris barrier typically consists of an open steel grillage or concrete slot structure that is anchored to bedrock in a confined section of the creek. Its function is to "filter" boulders and trees or root wads, while allowing smaller debris to pass.

Debris barriers or small debris basins are considered the most feasible option for intercepting debris above the developed areas along Panorama Drive. Possible sites are shown on Figure 3-3.

Providing temporary or permanent access to the debris barriers would represent the greatest implementation challenge.

For Mathews Creek, Cove Creek, and Cleopatra Creek, existing driveways could be used to access the back yards of the houses that are at risk from debris floods. From there, smaller machinery could work its way up the channels to the fan apexes where the creeks become gullied. Some property damage may be incurred to provide access to the sites and landscaping would probably be required following construction. Access to Gavles Creek is more problematic as the creek is confined by houses on either side. An access road could be constructed further east where there is a break in development (Figure 3-3). The most difficult site is Panorama Creek, where the channel is constrained by high ground to the west, a residential property to the east, and an addition to the house that has been constructed over the channel. An access road could be constructed along the Baden-Powell Trail, although such an option is not desirable from an environmental and aesthetic perspective.

The cost for a small debris barrier would be roughly $100,000 to $300,000 each, or about $1.0 million for all five (Panorama Creek to Cleopatra Creek).

Should debris barriers be chosen as the preferred debris flood mitigation structure, the steel grid would have to be closely spaced to retain relatively small (less than 10 cm diameter) debris. A debris barrier would need to be supplemented with downstream channel works in order to be fully effective.

A debris barrier is not considered a viable option at Francis Creek because of a lack of a suitable site.

Debris Flow Nets

Debris flow nets are a form of debris barrier that have been recently developed for creeks where the expected debris volumes are small (less than 1,000 m^3). Debris flow nets are a derivative of rockfall nets, which have been widely used to prevent rockfall from reaching development or infrastructure. The nets consist of interconnected steel rings that are positioned such that the net can expand dynamically to withstand impact forces.

An example of a debris flow net installation, for a different purpose, can be seen on Low Level Road in the City of North Vancouver. At the Deep Cove creeks, debris flow nets could be installed at the debris barrier sites shown on Figure 3-3.

If determined to be acceptable, debris flow nets could result in a significant cost saving compared to traditional debris barriers and would be a less invasive construction method. In fact, in view of access difficulties and aesthetic considerations, debris flow nets may be the only feasible form of debris barrier for some of the Deep Cove creeks. Depending on the location and the creek chosen, the debris flow nets could be as high as 3 m to 5 m and as wide as 10 m to 20 m. Access would remain a problem, but the nets could potentially be installed by hand and bolted to bedrock with pneumatic drills. There may be concern for public safety with the potential for children to use the nets as climbing devices.

DEFLECTION BERMS

A deflection berm (or training berm) can be used to deflect a debris flow or debris flood away from a development area and allow it to deposit in an area where it will cause minimal damage. Construction of a deflection berm depends on the availability of a suitable runout area on the fan. Deflection berms can be made to fit into the landscape in an aesthetically pleasing manner.

At the Deep Cove creeks, except Francis Creek, there are no suitable sites for deflection berms, because there is no undeveloped land to deflect a debris flow or debris flood toward. Any debris deflection would involve unacceptable transfer of risk. The only alternative is to acquire property and dismantle houses to provide space for debris deflection. This would have to be done in association with road works and is not considered a feasible option.

At Francis Creek, a deflection berm would be effective at 280 m elevation, where there is a possibility of channel avulsion into Martin Creek (Figure 3-2). Access to this site would be difficult, but could be achieved from an existing road that reaches a water tank at 230 m elevation and continues beneath the powerline corridor to an elevation of 250 m. Additional road construction would be required beyond this point. If a deflection berm was constructed, the design debris flow at Francis Creek would increase from 1,000 m^3 to 2,000 m^3, necessitating additional works along the creek channel to Indian River Drive. It would be necessary to also construct a debris basin above Indian River Drive in order to avoid increasing the risk at the Deep Cove Marina.

It would also be appropriate to construct a second deflection berm to protect the house located along the creek corridor upstream of Indian River Drive. The house is at risk from indirect debris impacts during a debris flow.

The cost for the deflection berms would be roughly $250,000 for the upper berm and $50,000 for the lower berm.

CHANNELIZATION WORKS

Channelization works can funnel a debris flow or debris flood through a critical reach to a downstream area where deposition will result in minimal damage. Implementation of channelization works depends on such a downstream area being present. In the case of the Deep Cove creeks, this would necessitate channelizing debris through the developed areas to Deep Cove. All of the creeks are already channelized to some degree as they flow through the developed area, but channel conveyance would have to be increased significantly in some cases to accommodate the design events. This would involve works on private property and, in some cases, structural modifications to existing houses. In addition, culverts along Panorama Drive would have to be increased in size or replaced by bridges due to debris blockage concerns. Given these negative aspects and the fact that the majority of the work would have to be carried out on private property, channelization works on their own are not considered a viable option.

3.6 CREEK MANAGEMENT MEASURES

This sub-section addresses some creek management measures that are appropriate for all the Deep Cove creeks. While a debris barrier or debris basin would contain the sediment in the event of a debris flood or debris flow, the water component could overwhelm some of the existing culverts along Panorama Drive or exceed the channel capacity. Accordingly, additional creek works would be required in conjunction with the chosen structure.

Determining the discharge of the water component is complicated due to the volume loss of the contained sediment and flow attenuation as the debris flood/debris flow impacts the mitigative structure. In light of no accepted standard methodology, the water component is suggested to be the 200-year return period flood (Francis Creek is an exception). In most cases, this value is approximately half the estimated peak discharge for the design debris flood. The implication is that the existing culverts would typically have sufficient capacity for the water component of the design events. However, channel capacity would need to be increased for Gavles Creek, Cove Creek and Cleopatra Creek above Panorama Drive where the channels flow beneath or adjacent to houses. Channel capacity should also be increased at the fan apexes of Panorama Creek and Mathews Creek to ensure that avulsions do not occur (immediately upstream of the homes).

In the case of Cleopatra Creek and Gavles Creek, channel works would result in significant property changes. If consent is obtained from the property owners, the estimated cost of the work would be approximately $50,000 to $100,000 for each creek. In the case of Gavles Creek, it may ultimately prove necessary to acquire one of the adjacent properties (#2679).

The channel reaches downstream of Panorama Drive would be very difficult to assess. All of the creeks flow adjacent to houses in concrete-lined channels downstream of the road. While the preference from an aesthetic and ecological perspective would be to establish buffers and natural riparian areas along all the creeks, the density of housing makes such works prohibitively expensive. From a flood perspective, upstream channel works should be sufficient to remove sediment and convey flows to the Panorama Drive culverts. From there, the concrete-lined channels should have sufficient capacity to convey flows to Deep Cove.

If a debris basin is constructed on Francis Creek above Indian River Drive, there would still be a need for downstream channel works. The 1,500 mm culvert at Indian River Drive would require upgrading (about $200,000). At the Deep Cove Marina, the optimum strategy would be to replace the box culvert with a larger culvert of bridge that would connect Panorama Drive with the Deep Cove Marina parking lot (estimated cost approximately $500,000). Some channel works or training berms may also have to be considered for locations where avulsions are possible.

3.7 SUMMARY OF ALTERNATIVE MITIGATION STRUCTURES

The suggested approach to hazard mitigation for the Deep Cove creeks is summarized as follows:

- prevent channel avulsions that result in interflow between watersheds;
- provide storage facilities for debris associated with design debris flood and/or debris flow events; and
- provide adequate channels to pass flood flows through the development areas to Deep Cove.

At the Deep Cove creeks, a combination of measures is identified as feasible and worthy of further consideration. The most promising measures are summarized in Table 3-1.

Table 3-1: Preferred Mitigative Measures for Deep Cove Creeks

Creek	Proposed Measures	Approximate Cost
Panorama Creek	Debris Barrier	$200,000
	Channel Works	$100,000
	Kai Creek Berm	$100,000
	Total Cost for Panorama Creek	**$500,000**
Mathews Creek	Debris Barrier	$200,000
	Channel Works	$100,000
	Total Cost for Mathews Creek	**$300,000**
Gavles Creek	Debris Barrier	$200,000
	Channel Works	$100,000
	Total Cost for Gavles Creek	**$300,000**
Cove Creek	Debris Barrier	$200,000
	Channel Works	$100,000
	Total Cost for Cove Creek	**$300,000**
Cleopatra Creek	Debris Barrier	$200,000
	Channel Works	$100,000
	Total Cost for Cleopatra Creek	**$300,000**
Martin Creek	No Works Required (assuming construction of Francis Creek deflection berm)	
	Total Cost for Martin Creek	**$0**
Francis Creek	Upper Deflection Berm	$250,000
	Lower Deflection Berm	$50,000
	Debris Basin	$400,000
	Indian River Drive Crossing	$200,000
	Channel Works at Marina	$500,000
	Total Cost for Francis Creek	**$1,400,000**

The total cost for all the suggested works on the Deep Cove creeks is about $3.1 million.

Section 4

Summary and Recommendations

KERR WOOD LEIDAL
associates limited
CONSULTING ENGINEERS

4. SUMMARY AND RECOMMENDATIONS

4.1 SUMMARY

The key points in this report are summarized as follows:

DEEP COVE CREEKS

1. For the purposes of this report, the Deep Cove creeks refer to Panorama Creek, Mathews Creek, Gavles Creek, Cove Creek, Cleopatra Creek, Martin Creek and Francis Creek.

2. Key features in the watersheds are Mount Seymour Road, Indian River Drive, and dense housing development along Panorama Drive.

HAZARD ASSESSMENT

3. There are several locations where interflow may occur between the various creek systems. These represent both natural and anthropogenic conditions where the creek channels may shift as a result of erosion or deposition.

4. Appendix D provides a hydrologic analysis that results in the following 200-year return period peak instantaneous flood flow estimates:

Creek	Peak Flow
Panorama Creek	4.2 m^3/s
Mathews Creek	4.5 m^3/s
Gavles Creek	2.4 m^3/s
Cove Creek	4.0 m^3/s
Cleopatra Creek	1.5 m^3/s
Martin Creek	3.1 m^3/s
Francis Creek	9.0 m^3/s

The above peak flow estimates provide some allowance for interflow between watersheds where this is considered to be likely.

5. A watershed investigation has been performed to identify potential debris flow and debris flood trigger mechanisms and determine the amount of available debris. A detailed watershed map has been produced (Figure 2-1) to document geomorphological conditions.

6. Appendix E provides an analysis of debris floods and debris flows, resulting in the following 500-year return period (10% chance in 50 years) magnitude estimates:

Creek	Event Type	Peak Discharge	Volume
Panorama Creek	Debris Flood	10 m^3/s	200 m^3
Mathews Creek	Debris Flood	9 m^3/s	150 m^3
Gavles Creek	Debris Flood	8 m^3/s	250 m^3
Cove Creek	Debris Flood	10 m^3/s	250 m^3
Cleopatra Creek	Debris Flood	4 m^3/s	100 m^3
Martin Creek	Debris Flow	25 m^3/s	1,000 m^3
Francis Creek	Debris Flow	25 m^3/s	1,000 m^3

7. While the 500-year return period events provide a reasonable basis for design, the potential impact of smaller and larger events also needs to be considered.

RISK ASSESSMENT PROCEDURE

8. For the purpose of this report, risk is defined as the combination of hazard probability and potential consequence (i.e. vulnerability to damage should an event occur).

9. Hazard probability is classified as ranging from low to very high, and can be estimated in terms of magnitude and peak discharge for each classification.

10. The consequence of a debris flow or debris flood depends on the size of the event and on conditions in the developed area. Consequence can be classified on a similar system as hazard probability (i.e. low to very high).

DEBRIS FLOOD CONSEQUENCE AND RISK AT PANORAMA CREEK, MATHEWS CREEK, GAVLES CREEK, COVE CREEK AND CLEOPATRA CREEK

11. A major debris flood on any of the Deep Cove creeks could result in direct or indirect debris impact to houses on Panorama Drive.

12. Under existing conditions, the debris flood risk is rated as medium high for a 500-year return period debris flood.

DEBRIS FLOW CONSEQUENCE AND RISK AT FRANCIS CREEK AND MARTIN CREEK

13. A major debris flow at Francis Creek could cause structural damage to buildings at the Deep Cove Marina and indirect debris impact to a house located upstream of Indian River Drive. A debris flow is also likely to cause damage to Indian River Drive. There is potential for loss of life.

14. A debris flow avulsion from Francis Creek to Martin Creek could result in direct or indirect damage to houses on Panorama Dive. There is potential for loss of life.

15. Under existing conditions, the debris flow risk is rated as high at Francis Creek and medium at Martin Creek for a 500-year return period debris flow.

ALTERNATIVE STRATEGIES FOR HAZARD MITIGATION

16. A wide range of strategies for debris flood and debris flow mitigation have been considered, including land use planning, warning systems, watershed management actions, and mitigative structures.

17. Watershed stabilization activities, incorporating bioengineering methods would be appropriate for some watershed areas.

18. Further development on Panorama Drive near creek channels should be subject to site-specific investigations to determine the need for mitigative measures, followed by implementation of any necessary measures.

19. A comprehensive culvert assessment should be undertaken for Mount Seymour Road, with a view to reducing the risk of culvert blockage and flood interflow between watersheds.

20. For the debris flood creeks (Panorama Creek, Mathews Creek, Gavles Creek, Cove Creek and Cleopatra Creek), risk mitigation would involve debris barriers above the Panorama Drive development and various channel works. These measures would cost between $300,000 and $500,000 per creek.

21. The debris flow risk at Francis Creek could be mitigated by construction of a 2,000 m^3 debris basin upstream of Indian River Drive. Additional works may include a deflection berm to prevent avulsion to Martin Creek, a second minor deflection berm to protect a house near Indian River Drive, upgrading the Indian River Drive culvert, and channel works at the Deep Cove Marina. The combined cost of these works at Francis Creek would be about $1.4 million.

22. With construction of the Francis Creek deflection berm, no mitigative measures would be required at Martin Creek.

23. The combined cost for risk mitigation at all the Deep Cove creeks would be about $3.1 million, not including any culvert upgrading that may be considered necessary on Mount Seymour Road.

24. The objective in implementing debris flow mitigation measures would be to reduce the overall level of risk (i.e. the residual risk) to at least medium low. Regardless of the alternative chosen, there will always remain at least some level of residual risk.

25. It would be appropriate to perform periodic watershed monitoring to identify major watershed instabilities.

4.2 RECOMMENDATIONS

It is recommended that the District disseminate the results of this study as follows:

1. Advise property owners and area residents regarding the contents of this report.

2. Submit copies of this report to the following agencies:

    - BC Ministry of Water, Land, and Air Protection;
    - BC Parks (with respect to operations at Mount Seymour Park); and
    - BC Ministry of Transportation (with respect to operation of Mount Seymour Road).

It is also recommended that the District proceed directly with risk mitigation actions as follows:

3. Restrict further development above the existing Panorama Drive development, unless detailed engineering studies conclude that such development can safely occur.

4. Ensure that appropriate site-specific mitigative measures are incorporated into any land development approvals (building permits, etc.) that are issued in the vicinity of the Deep Cove creeks.

5. Work with owners of the following key properties toward the implementation of on-site mitigative measures in the absence of comprehensive mitigative works: Panorama Creek (#2525), Mathews Creek (#2603), Gavles Creek (#2681, #2679), Cove Creek (#2735), and Cleopatra Creek (#2755). These properties are all situated above Panorama Drive and are at risk in the event of a medium probability debris flood.

6. Investigate alternative means for establishing an unobstructed channel on Gavles Creek at #2679 Panorama Drive.

7. Work with the BC Ministry of Transportation regarding completion of a comprehensive culvert assessment for Mount Seymour Road, followed by culvert upgrading as appropriate.

8. Consider posting warning signs on Indian River Drive to warn road users about the potential for creek hazards.

9. Consider the possibility of placing warning signs at the trail crossing as part of a broader initiative by the District.

If it is decided to implement mitigative measures at the Deep Cove creeks, then it is further recommended that the District:

10. Consult with residents and stakeholders prior to selecting a preferred alternative for implementation.

11. Make arrangements for construction of mitigative measures, including:

    - develop an appropriate funding mechanism;
    - determine future ownership of the works;
    - acquire any necessary property or right-of-way; and
    - establish maintenance requirements and responsibility.

12. Complete engineering design of mitigative works, with attention to environmental protection requirements, and with input from both residents and stakeholders.

13. Proceed with construction and follow up with post-construction monitoring.

In the event that mitigative measures are not implemented at the Deep Cove creeks in the short term, as a minimum it is recommended that the District:

14. Perform periodic monitoring of the watersheds to identify future instabilities that may warrant further public advisory or reconsideration of mitigative measures.

15. Consider the possible stabilization of key watershed areas.

4.3 REPORT SUBMISSION

Prepared by:

KERR WOOD LEIDAL ASSOCIATES LTD.

Matthias Jakob, Ph.D., P.Geo. Senior Geoscientist	Hamish Weatherly, M.Sc., P.Geo. Fluvial Geomorphologist

Reviewed by:

Mike V. Currie, M.Eng., P.Eng.
Project Manager

BIBLIOGRAPHY

Hungr, O., Evans, S.G., Bovis, M.J., and Hutchinson, J.N. 2001. A review of the classification of landslides in the flow type. Environmental and Engineering Geoscience VII(3): 221-228.

Jakob, M. 1996. Morphometric and geotechnical controls on debris flow frequency and magnitude in southwestern British Columbia. Unpublished Ph.D. thesis, University of British Columbia.

Jakob, M. and Jordan, P. 2001. Design floods in mountain streams – the need for a geomorphic approach. Canadian Journal of Civil Engineering 28 (3): 425-439.

Kerr Wood Leidal Associates Ltd. 1982. Report on Deep Cove – Dollarton Area. Report to District of North Vancouver.

Kerr Wood Leidal Associates Ltd. 1990. Overview Assessment of Mountainside Drainage Above Deep Cove. Draft report to District of North Vancouver.

Kerr Wood Leidal Associates Ltd., June 1996. Pre-Design Report on Debris Flow Mitigation Strategy for Upper Mackay Creek. Report to District of North Vancouver.

Kerr Wood Leidal Associates Ltd. and EBA Engineering Ltd. April 1999. Overview Report on Debris Flow Hazards. Report to District of North Vancouver.

Thurber Consultants Ltd. April 1983. Debris Torrent and Flooding Hazards - Highway 99, Howe Sound. Report to Ministry of Transportation and Highways, British Columbia.

Appendix A

Background Information on Debris Flows and Debris Floods

KERR WOOD LEIDAL
associates limited
CONSULTING ENGINEERS

Appendix A

Background Information on Debris Flows and Debris Floods

DEFINITIONS

Steep mountain creeks are typically subject to a spectrum of events, ranging from clear water floods to debris flows as shown by Figure A-1. Slides and falls are not confined to stream channels but can follow channels for part of their descent.

Debris flows are a form of rapid water-saturated channelized landslide. Debris flow velocity typically ranges between 5 and 10 m/s, but some fine-grained debris flows have been known to travel up to 20 m/s. They are most likely to occur on small, steep creeks that have abundant sources of debris. Debris flows are sometimes alternatively referred to as *debris torrents* where they are particularly coarse in nature and carry large amounts of organic debris or *mudflows* where they are particularly fine in nature. Volcanic debris flows are referred to as *lahars*.

Debris floods are a very rapid, surging flow of water, heavily charged with debris, in a steep channel (Hungr et al., 2001). The sediment may, furthermore, be transported in the form of massive surges, leaving sheets of poorly sorted debris ranging from sand to cobbles or small boulders. Sediment surges in debris floods are propelled by the tractive forces of water overlying the debris, and flow velocities are comparable to those of water floods. The discharge of debris floods is commonly 2 to 5 times higher than that of 200-year return period water floods (Jakob and Jordan, 2001).

DEBRIS FLOOD OCCURRENCE

Debris floods are a poorly understood process because they are rarely directly observed. While they can be caused by a variety of processes, the most commonly observed processes are breaches of temporary stream blockages caused by tributary debris flows or other landslide types. In such scenarios, debris flood discharge depends strongly on the composition and geometry of the landslide dam and the geometry of the floodplain downstream. The latter will determine the degree to which the debris flood will attenuate before reaching the point of interest (i.e. development). Therefore, the typical range for debris flood discharge of 2 to 5 times the 200-year return period peak water flood (Q_{200}) should only be used as a preliminary guideline (Hungr et al. 2001, Jakob and Jordan, 2001). In extreme cases, debris flood discharge may be more than five times the Q_{200}.

DEBRIS FLOW OCCURRENCE

Occurrences of debris flows in the B.C. Coast Mountains have been well documented since the early 1980's following a number of high profile events along the Squamish Highway. Debris flows tend to occur in wet weather, but are not necessarily coincident with record rainfall or flood events. Debris flow occurrence can be described by three consecutive processes as follows:

- *Initiation* where a mass movement is triggered at the source area in the creek headwaters. Possible trigger mechanisms include debris slides, logjam release, flood surges, and creek bed instability.

- *Transport* of the debris flow down the creek channel. The transport zone is typically scoured as the debris flow grows in size. A straight and uniformly steep gradient channel represents the most favourable transport condition.

- *Deposition* where either the channel becomes laterally unconfined, or the creek gradient flattens to the point that there is insufficient energy for continued movement. Depositional landforms are known as creek fans. Damage in creek fan areas during debris flow deposition can be catastrophic. The nature of the deposited material is highly variable, but typically covers a wide range from mud to boulders, and usually also includes a significant wood debris component. Debris flow deposition may also result in flooding of adjacent areas as a result of subsequent relocation of the creek channel.

DEBRIS FLOW PROBABILITY

While significant floods occur virtually every year on a creek system, debris flows are usually an intermittent occurrence. Typical debris flow recurrence intervals range from 5 to 50 years; however, this is highly variable. Debris flow occurrence can be put into perspective by considering geomorphological processes since the most recent glaciation about 10,000 years ago. In the centuries following glaciation, the landscape was unforested and littered with glacial debris. Debris flow activity is believed to have been considerably higher than today during this period. As the landscape became forested and watersheds stabilized, debris production and debris flow activity gradually decreased on a regional basis. However, debris flow activity may increase for any particular watershed as a result of natural or anthropogenic watershed instability. There is also reason to believe that if the present trend of increasingly wetter conditions in coastal areas continues, debris flow occurrence will increase in frequency and possibly magnitude.

In general, the frequency of debris flows on a particular creek is a function of:

- availability of debris supply sources that contribute materials to the main creek channel and its tributaries (necessity to differentiate drainage basins between material supply-limited vs. material supply-unlimited);
- degree of instability and level of activity of the debris supply sources;
- characteristics of the debris supply source (fine vs. coarse material, consolidated vs. unconsolidated);

- existence of potential triggers of debris flows (debris slides, rockfall, avalanches);
- capability of a creek channel to transport a debris flow (gradient, channel cross-section, longitudinal profile, channel roughness); and
- frequency of hydroclimatic events that have the capability of triggering debris flows.

As debris accumulates, a system gradually becomes "ripe" for a debris flow. The rate at which debris accumulates in a channel is a function of basin type.

BASIN TYPES

Recent research (Jakob, 1996) has identified two distinctly different basin types. One type, referred to as weathering-limited or supply-limited, is characterized by those basins that have a limited source of sediment and thus require recharge after a debris flow event for the next one to occur. In other words, even an exceptionally intensive storm will not trigger a debris flow if not enough sediment has accumulated to produce a debris flow. The other basin type is referred to as transport-limited or supply-unlimited. In those basins, there is a quasi-infinite amount of sediment available for transport and a debris flow can be triggered as soon as a critical climatic threshold (rainfall, rain-on-snow) is exceeded.

From the above description, it is clear that transport-limited basins experience a higher frequency of debris flows than weathering-limited basins. Examples for transport-limited basins are young volcanic complexes that rapidly shed material into the channel system, or basins with massive Quaternary deposits in the source area of debris flows. Weathering-limited basins are found primarily in slow weathering plutonic rock of the Coast Mountains.

Appendix B

Photographs

KERR WOOD LEIDAL
associates limited
CONSULTING ENGINEERS

Appendix B

Photographs

PANORAMA CREEK

Photo P-1 Typical view of Panorama Creek between Indian River Drive and Mount Seymour Road. March 2001.

Photo P-2 Panorama Creek approximately 350 m upstream of Panorama Drive. October 2001.

Photo P-3 Baden-Powell trail crossing of Panorama Creek. October 2001.

Photo P-4 House addition constructed across Panorama Creek above Panorama Drive. October 2001

Photo P-5 Approximately 20 m wide deposition zone located immediately upslope of Panorama Drive development. October 2001.

Photo P-6 Culvert inlet for Panorama Creek at Panorama Drive. A 600 mm overflow culvert is visible to the left of the main 1250 mm culvert. October 2001.

Photo P-7 Panorama Creek at creek mouth. May 2002.

MATHEWS CREEK

Photo M-1 Mathews Creek between Indian River Drive and Mount Seymour Road. March 2001.

Photo M-2 Upstream view of Mathews Creek approximately 200 m upslope of Panorama Drive. October 2001.

Photo M-3 Channelized section of Mathews Creek immediately upslope of residential property located above Panorama Drive. October 2001.

Photo M-4 Poorly confined section of Mathews Creek immediately upslope of residential property located above Panorama Drive. October 2001.

Photo M-5 View of Mathews Creek at creek mouth. Below Panorama Drive the creek flows in a concrete channel. May 2002.

GAVLES CREEK

Photo G-1 Downstream view of Gavles Creek from Baden-Powell Trail (crossing upstream of Indian River Drive). March 2001.

Photo G-2 Active sediment transport in Gavles Creek about 100 m downstream of Indian River Drive. March 2001.

Photo G-3 Gavles Creek about 200 m downstream of Indian River Drive. Sediment transport is significantly less than upstream reaches. March 2001.

Photo G-4 Gavles Creek flowing adjacent to residential property upstream of Panorama Drive. October 2001.

Photo G-5 Gavles Creek at Panorama Drive. May 2002.

Photo G-6 Upstream view of Gavles Creek from creek mouth at Deep Cove. May 2002.

COVE CREEK

Photo C-1 Tributary of Francis Creek at about 425 m elevation. March 2001.

Photo C-2 Overview of Cove Creek and Cleopatra Creek. October 2001.

Photo C-3 Cove Creek flowing adjacent to residential properties upstream of Panorama Drive. October 2001.

Photo C-4 Cove Creek flowing under residential property immediately upstream of Panorama Drive. May 2002.

Photo C-5 Upstream view of concrete channel that both Cove Creek and Cleopatra Creek discharge into below Panorama Drive. May 2002.

CLEOPATRA CREEK

Photo CL-1 Cleopatra Creek approximately 250 m upstream of Panorama Drive. October 2001.

Photo CL-2 Downstream view of Cleopatra Creek. The house in the background is located upslope of Panorama Drive. June 1997

Photo CL-3 Upstream view of Cleopatra Creek from Panorama Drive. Visible in the background is a 20 m long 1000 mm culvert that runs through the residential property. May 2002.

Photo CL-4 Culvert inlet of Cleopatra Creek at Panorama Drive. A 2 m drop leads to the culvert inlet and a steel grate has been placed on top to prevent debris blockage. May 2002.

MARTIN CREEK

Photo MAR-1 Upstream view of Martin Creek from Panorama Drive. May 2002.

Photo MAR-2

Photo MAR-3 Upstream view of Martin Creek from creek mouth. May 2002.

FRANCIS CREEK

Photo F-1 Confined upper reach of Francis Creek. October 2001.

Photo F-2 Bank erosion of fill slope at the first switchback of Mount Seymour Road. Approximate elevation 390 m. October 2001.

Photo F-3 Tension cracks on the surface of Mount Seymour Road at the lowermost switchback. Further erosion of the fill slope by Francis Creek could result in road failure. October 2001.

Photo F-4 Low gradient section of Francis Creek at about 320 m elevation. June 1997.

Photo F-5 Small concrete dam with box outlet located approximately 200 m upstream of Indian River Drive. A house is located to the right of the riprap. October 2001.

Photo F-6 Residential house located approximately 200 m upstream of Indian River Drive. Approximate elevation 225 m. October 2001.

Photo F-7 Debris barrier at culvert inlet of Francis Creek, Indian River Driver. October 2001.

Photo F-8 Bedrock section of Francis Creek downstream of Indian River Drive. June 1997.

Photo F-9 Overview of Francis Creek. October 2001.

Photo F-10 Concrete flume leading to Francis Creek box culvert at the Deep Cove Marina. June 1997.

Photo F-11 Deep Cove Marina and the box culvert outlet for Francis Creek. June 1997.

ADDITIONAL DEEP COVE CREEKS

Photo A-1 Upstream view of Kai Creek from Panorama Drive. May 2002.

Photo A-2 Upstream view of Convict Creek from Panorama Drive. May 2002.

Photo P-1
Typical view of Panorama Creek between Indian River Drive and Mount Seymour Road. March 2001.

Photo P-2
Panorama Creek approximately 350 m upstream of Panorama Drive. October 2001.

Photo P-3
Baden-Powell trail crossing of Panorama Creek. October 2001.

Photo P-4
House addition constructed across Panorama Creek above Panorama Drive. October 2001.

Photo P-5
Approximately 20 m wide deposition zone located immediately upslope of Panorama Drive development. October 2001.

Photo P-6
Culvert inlet for Panorama Creek at Panorama Drive. A 600 mm overflow culvert is visible to the left of the main 1250 mm culvert. October 2001.

Photo P-7
Panorama Creek at creek mouth. May 2002.

Photo M-1
Mathews Creek between Indian River Drive and Mount Seymour Road. March 2001.

Photo M-2
Upstream view of Mathews Creek approximately 200 m upslope of Panorama Drive. October 2001.

Photo M-3
Channelized section of Mathews Creek flowing adjacent to house upslope of Panorama Drive. October 2001.

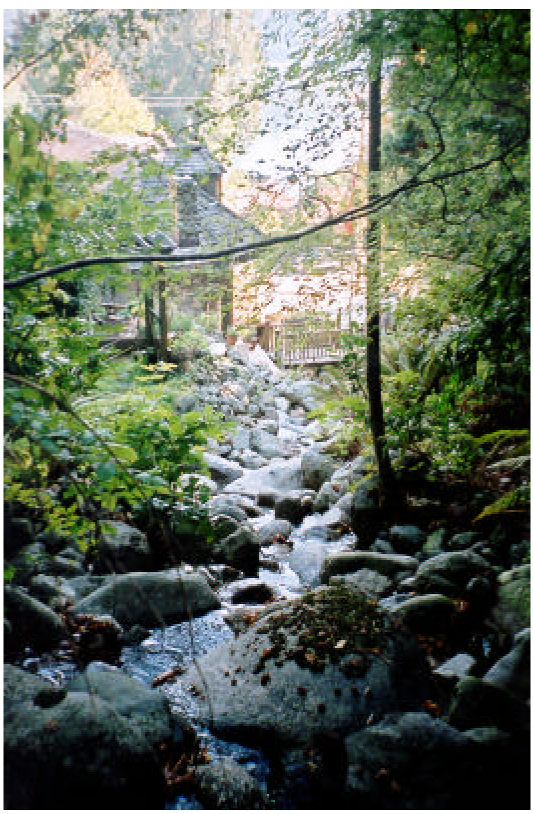

Photo M-4
Poorly confined section of Mathews Creek immediately upslope of residential property located above Panorama Drive. October 2001.

Photo M-5
View of Mathews Creek at creek mouth. Below Panorama Drive the creek flows in a concrete channel. May 2002.

Photo G-1
Downstream view of Gavles Creek from Baden-Powell Trail (crossing upstream of Indian River Drive). March 2001.

Photo G-2
Active sediment transport in Gavles Creek about 100 m downstream of Indian River Drive. March 2001.

Photo G-3
Gavles Creek about 200 m downstream of Indian River Drive. Sediment transport is significantly less than upstream reaches. March 2001.

Photo G-4
Gavles Creek flowing adjacent to residential property upstream of Panorama Drive. October 2001.

Photo G-5
Gavles Creek at Panorama Drive. May 2002.

Photo G-6
Upstream view of Gavles Creek from creek mouth at Deep Cove. May 2002.

Photo C-1
Tributary of Francis Creek at about 425 m elevation. March 2001.

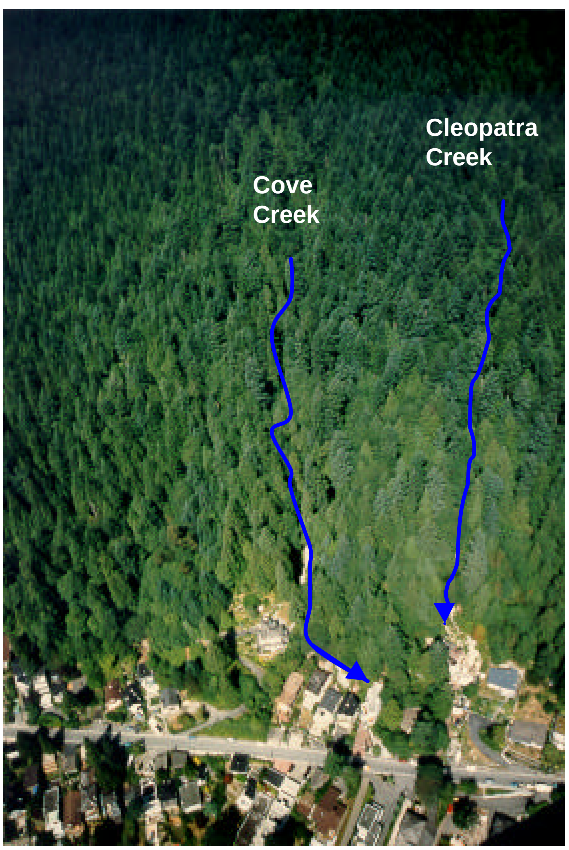

Photo C-2
Overview of Cove Creek and Cleopatra Creek. October 2001.

Photo C-3
Cove Creek flowing adjacent to residential properties upstream of Panorama Drive. October 2001.

Photo C-4
Cove Creek flowing under residential property immediately upstream of Panorama Drive. May 2002.

Photo C-5
Upstream view of concrete channel that both Cove Creek and Cleopatra Creek discharge into below Panorama Drive. May 2002.

Photo CL-1
Cleopatra Creek approximately 250 m upstream of Panorama Drive. October 2001.

Photo CL-2
Downstream view of Cleopatra Creek. The house in the background is located upslope of Panorama Drive. June 1997.

Photo CL-3
Upstream view of Cleopatra Creek from Panorama Drive. Visible in the background is the 20 m long 1000 mm culvert that runs through the residential property. May 2002.

Photo CL-4
Culvert inlet of Cleopatra Creek at Panorama Drive. A 2 m drop leads to the culvert inlet and a steel grate has been placed on top to prevent debris blockage. May 2002.

Photo MAR-1
Upstream view of Martin Creek from Panorama Drive. May 2002.

Photo MAR-2
Culvert inlet (1100 mm diameter) of Martin Creek at Panorama Drive. A small debris barrier is visible upstream of the culvert entrance. May 2002.

Photo MAR-3
Upstream view of Martin Creek from creek mouth. May 2002.

Photo F-1
Confined upper reach of Francis Creek. October 2001.

Photo F-2
Bank erosion of fill slope at the first switchback of Mount Seymour Road. Approximate elevation 390 m. October 2001.

Photo F-3
Tension cracks on the surface of Mount Seymour Road at the lowermost switchback. Further erosion of the fill slope by Francis Creek could result in road failure. October 2001.

Photo F-4
Low gradient section of Francis Creek at about 320 m elevation. June 1997.

Photo F-5
Small concrete dam with box outlet located approximately 200 m upstream of Indian River Drive. A house is located to the right of the riprap. October 2001.

Photo F-6
Residential house located approximately 200 m upstream of Indian River Drive. Approximate elevation 225 m. October 2001.

Photo F-7
Debris barrier at culvert inlet of Francis Creek, Indian River Drive. October 2001.

Photo F-8
Bedrock section of Francis Creek downstream of Indian River Drive. June 1997.

Photo F-9
Overview of Francis Creek.
October 2001.

Photo F-10
Concrete flume leading to the Francis Creek box culvert at the Deep Cove Marina. June 1997.

Photo F-11
Deep Cove Marina and the box culvert outlet for Francis Creek. June 1997.

Photo A-1
Upstream view of Kai Creek from Panorama Drive. May 2002.

Photo A-2
Upstream view of Convict Creek from Panorama Drive. May 2002.

Appendix C

Watershed Description

KERR WOOD LEIDAL
associates limited
CONSULTING ENGINEERS

Appendix C

Watershed Description

INTRODUCTION

This appendix provides a description of the Deep Cove Creek watersheds, including Panorama Creek, Mathews Creek, Gavles Creek, Cove Creek, Cleopatra Creek, Martin Creek and Francis Creek. Figure 2-1 is a detailed geomorphic map that should be used for reference with this appendix.

OVERVIEW OF WATERSHED CHARACTERISTICS

The Deep Cove creeks originate on the southeast slopes of Mount Seymour. These slopes constitute the southernmost extent of the British Columbia Coast Mountains. The slopes have been extensively altered by glaciation, most recently by the Fraser Glaciation, which reached its maximum some 18,000 years ago and ended with the melting of Fraser Glacier some 10,000 years ago.

Along with the scouring action of ice, which rounded slopes below approximately 2,000 m elevation, a mantle of glacial sediments was draped over the landscape. These glacial sediments are mostly composed of compact silty basal till, which was over-ridden by glacial ice throughout the Ice Age, and loose, mostly sandy ablation till, which was deposited from meltout within and on top of the former glaciers. Further downslope, pockets of glaciofluvial sediments, mostly ice margin features such as kame terraces, were deposited.

The distribution and characteristics of surficial sediments is important for sediment transport by fluvial and mass movement processes. Loose surficial sediments are easily eroded and entrained in fluvial and mass movement processes, while basal till behaves much like bedrock and is eroded very slowly.

The headwaters of the Deep Cove creeks are in forested terrain at elevations between 900 and 400 m. For the most part, the creeks are not well defined and can only be recognized on air photographs by deciduous riparian vegetation. This is a result of small drainage area and a lack of major structural discontinuities. Hence, the local geology favours the development of numerous creeks rather than a common drainage. An exception is between Panorama Drive and Indian River Drive, where Cove, Gavles, Mathews and Panorama Creeks are gullied below an elevation of 150 m.

Francis Creek differs from the other creeks with respect to surficial materials. Francis Creek is incised in bedrock for much of its length below 600 m elevation. The other Deep Cove creeks flow predominantly through dense basal till with the occasional outcrop of bedrock.

There is very little geomorphic activity in any of the creeks, evidenced by an absence of debris slides, rockfall and snow avalanche tracks. The substrate of the mainstem channels is completely obscured on air photographs by a closed tree canopy. The majority of the area was logged in the early 1900s, but is now covered by second growth forest.

Drainage Area

The drainage areas of the Deep Cove creeks at key locations are summarized as follows:

Table C-1: Drainage Areas of Deep Cove Creeks

Location	Panorama Creek (km^2)	Mathews Creek (km^2)	Gavles Creek (km^2)	Cove Creek (km^2)	Cleopatra Creek (km^2)	Martin Creek (km^2)	Francis Creek (km^2)
Total area (to Deep Cove)	0.49	0.51	0.37	0.36	0.19	0.19	1.35
Above Indian River Dr.	0.33	0.40	0.28	0.27	0.09	0.11	1.26
Above lower Mount Seymour Road	0.22	0.33	0.20	0.12	0.03	-	1.01

The four western creeks (Panorama, Mathews, Gavles and Cove) all have similar drainage areas, while Cleopatra and Martin Creeks are significantly smaller. The exception is Francis Creek, which is transitory between the relatively low gradient Deep Cove creek zone and the steeper Woodland Drainage Area to the northeast.

CREEK CHANNEL CHARACTERISTICS

This subsection provides a summary of creek channel characteristics. The general morphology of the Deep Cove creeks is first described (a majority the creeks are similar). A more detailed descriptions of each channel follows.

General Geomorphology

In the upper reaches, the creek gradients typically range between 10 and 20^o (Figure C-1). The creeks are generally poorly incised (Cove Creek is an exception) and material recruitment is low. The Deep Cove creeks are crossed by Mount Seymour Road several times in mid to upper reaches.

A pronounced feature common to all the Deep Cove creeks is an increase in channel gradient from about 14° to approximately 22° below about 150 m elevation. Above this elevation the creeks flow across a bench, referred to as the Indian River Drive benchlands. Below the bench, most of the creeks are gullied. The study creeks are poorly incised on the bench with sideslopes ranging from several to 10 m in length. The bench extends to an approximate elevation of 230 m. The change in gradient may be a legacy of Indian Arm Glacier, which appears to have maintained this elevation for some time as a similar slope break can be observed 20 km further northeast up Indian Arm. The slope break is not associated with a change in bedrock geology.

Between Indian River Drive and Panorama Drive, the creeks are incised to a variable degree in thick glacial deposits (mostly basal till and glaciofluvial deposits). The amount of incision can be expressed in the length of sideslopes and varies from less than 10 m up to 70 m (Cove Creek). The degree of incision probably reflects the history of streamflow for each creek. It is highly improbable that the current stream courses have persisted since deglaciation some 10,000 years ago. A more likely scenario is that flows have switched from one watershed into another in the past, particularly in the early stages of gully development when there was little incision into glacial materials. A general lack of confinement upstream of Indian River Drive (which would allow flow diversion) is consistent with this scenario. This pattern of creek development has also been aided by the lack of structural control on any of the creek alignments in the Deep Cove area.

Below Indian River Drive, active channel widths for the Deep Cove creeks typically range between 3 and 5 m. Francis Creek is an exception with channel widths reaching up to 8 m in places.

The lower reaches of all the study creeks flow through dense development. The development extends upslope from sea level (at Deep Cove) for about 100 to 125 m. Here, properties are located both above and below Panorama Drive, and many of the creeks have been significantly altered by channelization

Sediment Transport

Sediment loads in the Deep Cove creeks are characterized by gravels and cobbles up to 0.2 m in diameter, except Francis Creek, where boulders up to 0.3 m diameter are common. Sediment transport of the largest sizes appears to be relatively frequent (annual or biannual) based on a lack of observed moss and algae growth on individual clasts (clasts that have not been transported for several years tend to develop a dark weathered coloring on their surfaces that is referred to as patina). Larger boulders up to 1 m in diameter can be found along all creeks, but are usually locked in place and most likely represent in situ material from the surrounding till.

At several locations along Cove, Panorama, and Gavles Creeks, high flows have formed steep undercut slopes of silty to sandy compacted gravels. Material recruitment along these reaches is highly variable, but can be significant if an undercut sideslope collapses during a storm. Boulder size material is often transported for only short distances (several metres to several tens of metres) and intermittently stored in sediment wedges, often behind small logjams. These logjams either rot or break during subsequent floods, releasing their sediment load. In general, the sediment wedges are less than 5 to 10 m^3 in volume. The consequence is cyclical movement of sediment with long periods of relative quiescence being followed by bursts of high sediment transport.

Channel Profiles

Figure C-1 provides channel profiles for the Deep Cove creek channels. Slope statistics are provided in Table C-2.

Table C-2: Typical Channel Gradients of the Deep Cove Creeks

Location	Panorama Creek (°)	Mathews Creek (°)	Gavles Creek (°)	Cove Creek (°)	Cleopatra Creek (°)	Martin Creek (°)	Francis Creek (°)
u/s of Indian River Dr.	14	14	16	14	-	14	17
Indian River Drive to 150 m elevation	9	12	12	14	16	12	14
150 m elevation to Panorama Drive	18	19	18	17	17	19	15
Average Slope	15	15	17	15	16	15	16

As can be seen from the above table and Figure C-1, the channel gradients of Panorama, Mathews, Gavles, Cove, Cleopatra and Martin Creeks are very similar. Francis Creek has a greater variation in gradient, which is due to the presence of several waterfalls.

CHANNEL DESCRIPTIONS

The following is a detailed description of each of the study creeks.

Panorama Creek

Panorama Creek is the most westerly of the Deep Cove creeks described in this report. The creek originates above Mount Seymour Road where it becomes increasingly unconfined and narrow in an upslope direction (<2 m wide). Between the lower section of Mount Seymour Road and Indian River Drive, the creek is typically 3 to 4 m wide and the channel gradient ranges between 10 and 20°. Through this section, the creek is confined in a well-defined channel with 5 to 15 m long moderately sloped sidewalls (Photo P-1). Numerous ephemeral seeps are situated to the east of the main channel (Figure 2-1).

At Indian River Drive, the main channel of Panorama Creek flows through a wooden stave 1,200 mm culvert. Two ephemeral seeps (<1 m wide) that are tributary to the main channel are also culverted at the road (900 mm and 750 mm). Below the road, the creek discharges onto the Indian River Drive benchlands down to about 160 m elevation. At this location, the terrain is gentle and the channel gradient is about 6°. The creek is incised less than 1 m into the surrounding soils and is 2 to 3 m wide. Given the lack of incision, the creek tends to meander through the forest and splits into two channels approximately 50 m downstream of Indian River Drive (Figure 2-1). The more westerly of the channels carries about one-third of the discharge and flows parallel to the main channel until meeting up again in a gullied reach at an elevation of 135 m.

There is a least one location where flow from the east channel of Panorama Creek could avulse toward a small adjacent channel referred to as Kai Creek. A minor avulsion is known to have occurred in the 1990s.

Further downstream Panorama Creek becomes increasingly confined in a gully with sideslopes of 15 to 40 m in length and slope gradients ranging between 20 and 35^o. Through this reach, the channel has a gradient of 15 to 25^o and is typically about 3 to 5 m wide. Wider sections are not uncommon and correspond with large woody debris that form sediment wedges and divert flow to the channel margins (Photo P-2). On several steeper sections, the creek flows over bedrock. However, the majority of the channel substrate is characterized by interlocking cobbles and boulders that result in a step-pool morphology that is typical for steep creeks.

Panorama Creek is intersected by the Baden-Powell trail at an elevation of approximately 70 m where it is crossed by an old footbridge. The footbridge has minimal capacity for peak flows with less than 0.75 m of clearance (Photo P-3). The creek emerges from the gully immediately upstream of Panorama Drive where it flows in a 3 to 4 m wide channel parallel to a house (#2525). An addition to the house has been built over the channel as shown on Photo P-4. Significant alterations have been made to the channel including partial grouting of the channel bed and construction of a 1 to 1.5 m high concrete wall along the left bank. The concrete wall extends from the upstream end of the property down to Panorama Drive. Through this reach, the channel has a cross-section area of 4.5 m^2.

While there is sufficient capacity for peak discharges to flow in the channel adjacent to the house, the creek could avulse into the back yard in the event of a debris flood. The right bank of the creek rises sharply to high ground and there is no risk of overflows in that direction. Approximately 20 m upstream of this point, a 20 m wide deposition zone is evidence of previous high sediment transport rates (Photo P-5).

At Panorama Drive, the creek flows through a 1,250 mm culvert with additional capacity provided by a 600 mm overflow culvert (Photo P-6). The culverts discharge into a 2 m wide concrete-lined channel that extends a majority of the 50 m distance to Deep Cove. Houses #2514 and #2520 are situated on either side of the concrete channel (Photo P-7).

Mathews Creek

At the lower section of Mount Seymour Road, Mathews Creek flows in two channels, which intersect approximately 75 m below the road. Most of the flow is in the west branch. Above the road, the west branch is poorly confined and is generally incised less than 0.5 m into the underlying till. While this allows for frequent avulsions, the creek does not have sufficient streampower (approximately 2 to 3 m wide) to transport significant sediment volumes. The creek intersects a BC Hydro powerline about 75 m upslope of Mount Seymour Road. The powerline right-of-way is about 75 m wide, on which a rough access road is located. Mathews Creek crosses the road via a ford.

Below Mount Seymour Road, the creek is confined but the sideslopes are generally less than 10 m in length with gentle to moderate gradients. Mathews Creek is crossed by the Baden-Powell trail at several locations as the trail switchbacks toward Mount Seymour Road. The bed is predominantly composed of cobbles and boulders but the creek occasionally flows over bedrock (Photo M-1).

At Indian River Drive, Mathews Creek flows through a 600 mm culvert before reaching the benchlands. Here the channel gradient ranges between 5 and 10^o but the creek remains well confined by 10 m long sideslopes with moderate gradients. Further downslope, Mathews Creek is considerably less incised than Panorama Creek. The creek is typically 2 to 3 m wide and confined by 10 to 20 m long sideslopes with moderate gradients (Photo M-2). The Baden-Powell trail intersects the creek at an approximate elevation of 80 m.

Mathews Creek has been significantly altered by residential construction along Panorama Drive. Above the road, Mathews Creek flows through the property of house #2603. A driveway is situated to the right of the creek while the house is to the left (Photo M-3). Along this reach, the creek flows through a 1.5 to 2 m wide channel with a cross-sectional area of about 3 m^2. Both banks are lined with large cobbles and boulders, which are probably cemented in place. A wooden footbridge and a concrete walkway, situated approximately 15 m apart, provide access to the house from the driveway. The channel gradient is about 18^o at this location.

The back yard of the house extends about 85 m upslope of Panorama Drive, which roughly corresponds to the fan apex. While most of the flow is directed to the right at this location, an old side channel is visible on the left hand side that leads to a gazebo (Photo M-4). Because the creek is not well incised at this location, a debris flood could result in floodwaters being directed toward the back of the house.

At Panorama Drive, the creek flows through a 1,200 mm by 2,000 mm box culvert. The culvert discharges into an approximately 2 m wide concrete channel that extends about 50 m down to Deep Cove (Figure 1-3). A house is situated to the left of the concrete channel while a 25 m wide right-of way is to the right (Photo M-5).

Gavles Creek

Gavles Creek is poorly confined above the upper section of Mount Seymour Road. Here, the creek is generally 2 to 3 m wide and incised less than 1 m into the surrounding soils. Below this location, the creek consists of two branches that are separated by less than 20 m. Most of the flow is contained within the west branch and the east branch contains little or no flow during low discharge. The west branch is characterized by a 3 to 4 m wide channel with a gradient ranging between 10 and 20^o. The lowest gradient reach is located immediately upstream of Indian River Drive.

Between Indian River Drive and a crossing of the Baden-Powell trail (a distance of about 250 m), Gavles Creek is characterized by active sediment transport of gravel and fine cobble (Photo G-1). Although the creek is not incised significantly (15^o sideslopes, 5 to 10 m in length), bank erosion supplies the sediment to the creek. For example, about 125 m above the Baden-Powell trail crossing, the creek has incised 2.5 m into the dense till, forming near vertical sidewalls for a 15 m length of channel. Sediment from this erosion has subsequently been deposited downstream of the Baden-Powell trail. Above this incised section, the creek flows through the powerline right-of-way and there are no further sediment sources.

At Indian River Drive, Gavles Creek flows through two 750 mm culverts. Active sediment transport is apparent below the road and the creek is confined by gentle to moderate slopes (Photo G-2). Immediately below the road, the channel gradient averages about 5^o, and increases to over 15^o within a couple hundred metres. As the channel gradient increases, the degree of confinement increases and the sediment transport rate decreases (Photo G-3).

Given the clean scoured nature of the deposited sediment, sediment transport must be occurring on a frequent (near annual) basis. Over time, it is expected that this sediment will stabilize as larger clasts form an interlocking pattern and wedges form behind woody debris jams. KWL personnel first noted unusually active sediment transport in Gavles Creek about 10 years ago during a drainage study. While sediment sources are evident, the question remains as to why sediment transport is more active in Gavles Creek than in other Deep Cove creeks - the creeks share similar geomorphic characteristics and drainage areas are also relatively similar. The answer may be that there is less instream woody debris in Gavles Creek. The Deep Cove creeks are characterized by frequent sediment wedges (on average about every 20 m or five channel widths) that form behind woody debris jams. Debris jams can be an important stabilizing influence on sediment transport in steep mountain creeks and the observed active sediment transport in Gavles Creek may reflect a lower density of these structures.

Upstream of Panorama Drive, Gavles Creek flows adjacent to two properties. At the upstream limit of development, the creek emerges from confinement to flow parallel to property #2681 (Figure 1-3). Here the creek is a couple of metres wide and has a cross-sectional area of approximately 2 m^2. The channel is confined by a 1 m high concrete wall on the left bank and a stone wall/high ground on the right bank (Photo G-4). A further 30 m downstream, the creek flows through property #2679. Here the creek flows under a wooden deck for about 10 m before emerging into an engineered channel that lies on the west side of the property. At this location, the channel is about 1 m wide and consists of a concrete bed with stone walls on either bank (Photo G-5). Channel avulsions are likely through this reach due to a limited channel capacity, particularly under the deck where the cross-section area is only about 1 m^2.

At Panorama Drive, Gavles Creek flows through a 1,000 mm culvert before emerging into an approximately 2 m wide concrete lined channel that extends down to Deep Cove (Photo G-6). This portion of the creek flows between houses #2672 and #2666.

Cove Creek

Cove Creek is located east of Gavles Creek and west of Cleopatra Creek. It originates above the upper section of Mount Seymour Road at an elevation of approximately 450 m. On review of the local topography (Figure 2-1), it would appear that the drainage area of the watershed would extend further upslope. However, a site visit revealed the presence of an upstream tributary channel that runs parallel to Mount Seymour Road and discharges into Francis Creek (Photo C-1). A small portion of the flow in the tributary channel escapes to the south into the Cove Creek watershed at an elevation of about 480 m. Here the channel is not well incised and avulsions are possible (Figure 2-1).

Cove Creek becomes well defined downstream of Mount Seymour Road. Between this road and Indian River Drive, the creek is generally 2 to 3 m wide and is confined within bedrock canyon sections (3 to 6 m of incision) or by 5 to 15 m long sideslopes with gradients of up to 35^{o}. Toward Indian River Drive, the creek becomes less confined eventually flowing onto a 10 m wide flat where the channel has a step-pool morphology with a number of sediment wedges formed by woody debris.

At Indian River Drive, Cove Creek flows through a 1,800 mm by 1,200 mm box culvert. The culvert was constructed in 1995, replacing a 1,500 mm wood stave culvert. Immediately downstream, the average channel gradient is 17° and the channel is generally underlain by bedrock. About 100 m below the road, several sediment wedges have formed behind small log jams that contain several cubic metres of gravel. Below this point, Cove Creek becomes increasingly incised with 35° sideslopes that have slope lengths of up to 70 m. At about 80 m elevation, a small sideslope failure in glacial till has deposited approximately 100 m^3 of material into the main channel forming a boulder apron. The 5 m high escarpment is now ravelling and acts as a continuous source of sediment. The channel gradient is approximately 20^{o} at this location.

A wooden footbridge spans the creek at an elevation of approximately 30 m. The channel capacity at this location is about 18 m^2 and an avulsion is very unlikely. Below the bridge, the creek flows in a southeastery direction skirting the backyards of several properties (Photo C-2). Avulsions are unlikely through this section, as the cross-section area is about 10 m^2 (Photo C-3). Before reaching Panorama Drive, the creek flows under house #2735. At this location, a 1.5 m wide concrete channel with stone walls has been constructed under the house (Photo C-4). The channel is 1 to 1.5 m high and two debris barriers (that consist of four posts less than 0.5 m in height) have been incorporated into the design.

At Panorama Drive, Cove Creek flows through a 1,500 mm concrete culvert with a rock headwall. The culvert outlet does not daylight immediate below the road. Instead the culvert continues in a southeasterly direction where it joins the culvert of Cleopatra Creek. The combined discharge continues in a culvert to the southeast before discharging into a 25 m long concrete channel situated between two houses (Photo C-5). The concrete channel is several metres wide and a couple of metres high.

Cleopatra Creek

Along with Martin Creek, Cleopatra Creek has the smallest watershed area of the study creeks (0.2 km^2). Not surprisingly, the creek is poorly defined in the vicinity of Indian River Drive (600 mm culvert). Cleopatra Creek becomes more confined downstream of 100 m elevation where the channel gradient is about 20^o. Between 100 m and 40 m elevation, the creek is confined by 10 to 25 m long sideslopes with gradients ranging between 30 and 45^o (Photo CL-1). Sediment is relatively abundant through this section with small sediment wedges (< 2 m^3) forming behind woody debris.

At about 40 m elevation, the creek flows into the back yard of house #2755 (Photo CL-2). The creek initially flows through a dense growth of blackberries and the left bank is a near vertical exposure of dense till that is several metres high. The cut bank is less than 20 m in length and immediately downstream the creek flows under a workshop where the channel capacity is only about 1.5 m^2. The creek then flows through a 20 m long, 1,000 mm culvert, above which a patio has been constructed (Photo CL-3). A short 10 m section of riprapped channel connects the culvert to the inlet of a 1,000 mm culvert that crosses Panorama Drive. The culvert inlet consists of a 2 m drop from the channel and a metal grate has been placed on top of the opening to prevent debris blockage (Photo CL-4).

The culvert connects with a culverted section of Cove Creek before discharging into a 25 m long concrete channel situated between two houses (Photo C-5). The concrete channel is 2 to 3 m wide and a couple of metres high.

Martin Creek

Martin Creek lies to the east of Cleopatra Creek and has a similar drainage area (0.2 km^2). Despite its small drainage area, the creek is well confined in the vicinity of Indian River Drive. At this location, the creek is less than 1 m wide but it is confined in a gully with sideslopes up to 20 m in length and gradients ranging between 20^o and 30^o. Given the lack of drainage area upstream, the well defined gully would appear to be an anomalous geomorphic landform. However, Francis Creek is poorly confined at an elevation of 280 m and there is the potential for flood flows or debris flows to avulse into the drainage of Martin Creek. Such events have obviously occurred in the past given the degree of incision observed in Martin Creek.

Martin Creek crosses Indian River Drive through a 600 mm wooden culvert and the creek remains well confined down to an elevation of 100 m. Here the channel gradient decreases to between 6^o and 10^o, after ranging between 14^o and 20^o further upslope. After crossing a powerline, the channel gradient increases again and Cove Creek flows over a 10 m high waterfall at an elevation of approximately 75 m. At the base of the waterfall, the creek is confined within a broad drainage with sideslope lengths exceeding 40 m. About 100 m further downslope, the creek flows to the immediate west of a residential property, house #2833. The 40 m length of channel that lies adjacent to the house has been lined with native rounded boulders (Photo M-1) and the cross-section area varies between 3 and 6 m^2.

At Panorama Drive, Cove Creek flows through a 1,100 mm culvert. The culvert inlet has a concrete headwall and wingwalls, and a debris barrier that consists of four metal posts about 0.5 m high (Photo M-2). Below the road, the creek flows between houses #2802, 2814 and 2820. The channel bed consists of rounded boulders and the right bank of the creek lies flush against house #2802 (Photo M-3).

Francis Creek

Francis Creek is the easternmost creek of the Deep Cove creeks. With a total length of 2.3 km and a watershed area of 1.2 km^2, it is also the largest of the Deep Cove creeks. Francis Creek originates above 900 m elevation near the upper switchback of Mount Seymour Road (Figure 2-1). The channel gradient in this area varies between 18° and 25°. A significant tributary to the west of the main channel and above 450 m elevation actually drains into Francis Creek although some flow escapes into the Cove Creek watershed due to poor confinement.

Bedrock exposures are common in the mid to upper reaches and the creek is well confined in a gully between 675 m and 280 m elevation (Photo F-1). The gully sideslopes are steep and have slope lengths ranging between 10 and 60 m. Debris slides are most likely to occur on the left side (east) of Francis Creek where the sideslopes are generally steeper and are overlain by a veneer of colluvium.

The mainstem channel of Francis Creek steepens (35^o channel gradient) at 475 m and drops over a 60° waterfall just above the lowermost switchback of Mount Seymour Road. At the bottom of the waterfall, a debris cone suggests periodic deposition by debris floods or debris flows. A little further downstream, Francis Creek flows directly against the fill slope of Mount Seymour Road at the first switchback (elevation 390 m). Sidecast material on the outside of the switchback is oversteepened and is currently being undercut by Francis Creek (Photo F-2). Subsequent settlement of the fill has resulted in cracking of the asphalt road pavement paralleling the creek (Photo F-3). Tensions cracks are characteristic precursors of potential failures of road fill.

Downslope of Mount Seymour Road, Francis Creek remains confined within a well defined gully but the channel gradient decreases significantly (ranging between 13^o and 15°). The lower channel gradient results in increased sediment deposition (Photo F-4). For example, a log jam containing approximately 80 m^3 of sediment is located at 345 m elevation.

A key location is a channel bend at 280 m elevation, where a debris flood or debris flow could avulse to the south into the watershed of Martin Creek (Figure 2-1). An incised channel toward the south and loose rounded boulders are evidence of previous avulsions. The channel gradient at the channel bend is approximately 8^o. Shortly below this section, Francis Creek drops over a steep (70°) 20 m high waterfall. The falls appears to have been the location of an old water intake, evidenced by an abandoned 250 mm steel pipe.

At 225 m elevation, the channel is narrowed by a stacked rock wall and flows through a narrow weir (which would likely be destroyed during a debris flow, Photo F-5). Immediately upstream, a house is located some 10 m west of the present channel and a footbridge spans the creek (Photo F-6). Further downstream, Francis Creek flows over bedrock at a gradient between 10° and 15° before reaching Indian River Drive at 195 m elevation. A small debris barrier has been erected about 5 m upstream of the culvert (Photo F-7). The barrier consists of six metal posts that are approximately 0.5 m high. The road fill on Indian River Drive is protected by grouted riprap and the creek flows through a 1500 mm concrete culvert.

Downstream of Indian River Drive, the channel gradient of Francis Creek steepens to approximately 25 to 30° and the creek flows mostly over bedrock down to the Deep Cove Marina (Photo F-8, F-9). Upslope of the marina, Francis Creek is directed into a concrete channel that flows into a 1500 mm by 1900 mm box culvert (Photo F-10). The box culvert runs under the parking lot of the marina before discharging into Deep Cove (Photo F-11).

Additional Deep Cove Creeks

In addition to the main creeks identified, there are several small creeks situated within the study area (Figure 1-3). Kai Creek is an ephemeral creek situated between Panorama Creek and Mathews Creek. This creek drains a small watershed area and is less than 1.0 m wide. At Panorama Drive, Kai Creek flows between houses #2553 and #2559 within a 0.5 to 1.0 m wide concrete trough (Photo A-1). The creek then flows through a 500 mm culvert and discharges into a similar concrete channel on the downslope side of Panorama Creek where it flows through a narrow gap between houses.

Convict Creek is a similar sized creek located between Gavles Creek and Mathews Creek. Upslope of Panorama Drive, the creek is contained within a 0.5 to 1.0 m wide stone wall trough situated between houses #2643 and #2659 (Photo A-2). It then flows through an 800 mm culvert, the entrance of which is protected by a small debris barrier consisting of 0.3 m high metal posts. Below Panorama Drive, Convict Creek flows in a similar concrete trough that has been constructed in a narrow gap between two residential properties.

Neither creek is judged to be prone to debris floods due to their small size and lack of incision upstream of Panorama Drive. There is potential for an avulsion to occur from Panorama Creek to Kai Creek that could result in a hazard at Kai Creek.

A third creek is situated to the west of Martin Creek. This un-named creek is more aptly described as a seep. About 10 m upslope of Panorama Drive, the seep flows through a 500 m culvert that does not daylight until reaching Deep Cove.

FAN AREAS

Deep Cove Creeks

The Deep Cove creek fans are densely developed and significantly altered by construction. The typical cone-shaped morphology that characterizes fans is not apparent on any of the creeks. A lack of a distinct morphology is due to house construction and property landscaping along Panorama Drive, and the fact that most creeks have small sediment loads that do not promote the formation of well defined fans. In contrast, small coalescing submarine fans associated with floods are noticeable at the mouth of the creeks at low tide.

Both the larger fan complexes and the small creek mouth fans are still active. The larger fan complexes are now not as much constrained by topography as by retaining walls, concrete barriers, wooden decks, garages or houses. Despite these structures, areas adjacent to the creeks are still at risk from debris floods or flooding.

Francis Creek

The fan of Francis Creek has been altered by construction of the Deep Cove Marina parking lot. A retaining wall on the south side of the creek prevents flooding of Panorama Drive during normal peak flow events and a box culvert conveys the creek flow to Indian Arm. The Marina store, gas station and additional parking areas are located on the fan.

Appendix D

Hydrologic Analysis

KERR WOOD LEIDAL associates limited
CONSULTING ENGINEERS

Appendix D

Hydrologic Analysis

INTRODUCTION

Peak flow estimates are required to assist with the debris flow and debris flood assessment of various creek systems in the District of North Vancouver. This appendix provides peak instantaneous flow estimates for the Deep Cove creeks: Panorama Creek, Mathews Creek, Gavles Creek, Cove Creek, Cleopatra Creek, Martin Creek and Francis Creek.

PEAK FLOW ESTIMATION

The two primary methods available for estimating peak flows at the study site are regional analysis and rainfall-runoff modelling.

Regional analysis estimates peak flows by using hydrometric data from regional stations. This data is used to determine a streamflow pattern and a frequency distribution of floods which are representative in the region. Rainfall-runoff analysis uses design storms and physical watershed characteristics to calculate peak flow estimates. This appendix focuses on regional analysis.

REGIONAL ANALYSIS

Water Survey of Canada operates or has operated a number of hydrometric stations in the region. Table D-1 summarizes the non-regulated stations on small watersheds that have more than 10 years of record.

Table D-1: Hydrometric Stations

Station Name	Station Number	Area (km^2)	Period of Record	Flow Data Available
Mackay Creek at Montroyal Boulevard	08GA061	3.63	1971,1973, 1974 - present	25 years of max. inst, 27 years of max. daily
Noons Creek at Meridian Substation Road	08GA065	2.59	1976 – 1996	16 years of max. inst., 16 years of max. daily

Notes:
Maximum Instantaneous is the maximum flow at any instant of time in the year of record
Maximum Daily is the maximum average flow for one day in the year of record

Both of these stations have reasonably long records and are judged to be suitable for regional analysis. It should be noted, however, that the two stations have some possibly significant physical differences from the Deep Cove area. These include drainage area and the type of ground cover (Mackay has an urban component, Noons has a deforested component, while the study creeks are relatively undisturbed and mostly forested).

A regional hydrometric frequency analysis for Mackay Creek and Noons Creek was completed using the Consolidated Frequency Analysis (CFA) software package. CFA provides the results of the following methods of frequency analysis: Generalized Extreme Value, Three Parameter Lognormal, Log Pearson Type III, Wakeby and Nonparametric.

The two selected stations were analyzed using the available maximum instantaneous data as detailed in Table D-1 and the resulting peak flow estimates for various return periods are summarized in Table D-2 (the values shown represent the average of all five methods). The average unit peak flow rate for the two selected stations is also listed.

Table D-2: Regional Analysis Results

Return Period (years)	Mackay Creek (area = 3.63 km^2)		Noons Creek (area = 2.59 km^2)		Average Unit Flow (m^3/s/km^2)
	Peak Flow (m^3/s)	Unit Flow (m^3/s/km^2)	Peak Flow (m^3/s)	Unit Flow (m^3/s/km^2)	
2	5.9	1.6	7.3	2.8	2.2
5	8.8	2.4	9.7	3.8	3.1
10	10.8	3.0	11.5	4.4	3.7
100	18.5	5.1	16.6	6.4	5.8
200	20.8	5.7	18.1	7.0	6.4

Based on the average unit peak flow rate for the two selected stations, Table D-3 provides peak flow estimates for the Deep Cove creeks.

Table D-3: Peak Instantaneous Flow Estimates for Deep Cove Creeks

Return Period (years)	Panorama Creek	Mathews Creek	Gavles Creek	Cove Creek	Cleopatra Creek	Martin Creek	Francis Creek
	Peak Flow (m^3/s)	Peak Flow (m^3/s)	Peak Flow (m^3/s)	Peak Flow (m^3/s)	Peak Flow (m^3/s)	Peak Flow (m^3/s)	Peak Flow (m^3/s)
	0.49 km^2	0.51 km^2	0.37 km^2	0.36 km^2	0.19 km^2	0.19 km^2	1.35 km^2
2	1.1	1.1	0.8	0.8	0.4	0.4	3.0
5	1.5	1.6	1.1	1.1	0.6	0.6	4.2
10	1.8	1.9	1.4	1.3	0.7	0.7	5.0
100	2.8	3.0	2.1	2.1	1.1	1.1	7.8
200	3.1	3.3	2.4	2.3	1.2	1.2	8.6

The peak flows tabulated above are for the primary watershed area, where flow is not diverted from one watershed to another. However, there is the potential for culverts to become blocked during a storm event and for the stream flow to be diverted into another watershed. Such an occurrence is not likely to occur along Indian River Drive, as the road grade is relatively level and drainages are well defined. Hence, overflows would be directed back into the channel on the downslope side of the road.

Along the lower section of Mount Seymour Road, however, the road grade is relatively steep and a blocked culvert would result in water being diverted down the ditch toward the next culvert. For Cove Creek, a blocked culvert along the main channel would likely be intercepted by one of two culverts within the same watershed (Figure 2-1). A blocked culvert along Gavles Creek, however, would be diverted into the east channel of Mathews Creek. Similarly, the discharge of the west channel of Mathews Creek could be diverted into Panorama Creek. These scenarios are similar to the 1995 event on Panorama Creek where a 900 mm culvert along lower Mount Seymour Road became blocked during a storm, resulting in diversion into Gallant Creek and subsequent flooding. There is also the potential for a western tributary of Francis Creek to avulse into Cove Creek at about 480 m elevation (see Appendix C).

There is also the potential for peak flows in Francis Creek to be diverted into Martin Creek at an approximate elevation of 280 m (see Figure 2-1). It is estimated that up to one-third of the flow could be diverted at this location, but only during a significant storm (100 or 200-year return period).

Given the potential for flow diversions, a second set of effective peak flow estimates have been calculated for Panorama Creek, Mathews Creek, Cove Creek and Martin Creek based on a larger drainage area (Table D-4). Significant flow diversions are not expected into Gavles Creek, Cleopatra Creek or Francis Creek.

Table D-4: Effective Peak Instantaneous Flow Estimates for Deep Cove Creeks

Return Period	Panorama Creek	Mathews Creek	Cove Creek	Martin Creek
	Peak Flow (m^3/s)	Peak Flow (m^3/s)	Peak Flow (m^3/s)	Peak Flow (m^3/s)
	0.65 km^2	**0.71 km^2**	**0.62 km^2**	**0.49 km^2**
2	1.4	1.6	1.4	-
5	2.0	2.2	1.9	-
10	2.4	2.6	2.3	-
100	3.8	4.1	3.6	2.8
200	4.2	4.5	4.0	3.1

The results of the regional analysis should be used with caution due to the small number of stations available for comparison and due to the differences between the watershed characteristics. In addition, it should be recognized that a linear relation is assumed between drainage area and flow due to the relatively small difference between the drainage areas of the study creeks and the two reference creeks.

SELECTION OF PRELIMINARY DESIGN PEAK FLOWS

As the 200-year return period is the standard for flood protection works in B.C., the design flows for the Deep Cove creeks are as follows:

Table D5: Preliminary Design Flows for Deep Cove Creeks

Creek	Q_{200} (m^3/s)
Panorama Creek	4.2
Mathews Creek	4.5
Gavles Creek	2.4
Cove Creek	4.0
Cleopatra Creek	1.5
Martin Creek	3.1
Francis Creek	9.0

The estimates for Panorama Creek, Mathews Creek, Cove Creek, and Martin Creek represent the effective peak flow estimates allowing for the identified flow diversions. The other peak flow estimates have been rounded up slightly to account for uncertainty and a potential increasing trend in precipitation in coastal B.C. These estimates are considered adequate for design of works that are not sensitive to design flow. Caution should be applied in using these estimates for other purposes.

LIMITATIONS

Hydrologic modelling is an imprecise exercise. Typically, short records are extrapolated to long time periods without a sound scientific basis to do so. This extrapolation is done out of necessity because design flows are needed for various purposes.

In the case of the frequency analysis for the Deep Cove creeks, 25-year and 16-year hydrometric records are extended to 200 years. Both extrapolations assume a stationarity of data (there are no long-term changes in the rainfall and runoff pattern), which is unlikely in a 200-year period. The precision at which the statistical analysis is reported in this appendix emanates from the mathematical method used, and does not reflect a high degree of accuracy.

It is important to note that the design flood discharge for mountain creeks is typically lower than the debris flow or debris flood discharge. Therefore, design of channel works, bridges and culverts should not be based on the design flood event but on the process that yields the highest discharge magnitude. Debris flow and debris flood magnitude and frequency for the Deep Cove creeks are detailed in Appendix E.

Appendix E

Debris Flow and Debris Flood Probability and Magnitude

KERR WOOD LEIDAL
associates limited
CONSULTING ENGINEERS

Appendix E

Debris Flow and Debris Flood Probability and Magnitude

INTRODUCTION

This appendix provides a comprehensive assessment of debris flow and debris flood hazard at the Deep Cove creeks, with estimates of total volume and peak flow for various return periods.

The Deep Cove creeks are typically debris flood creeks because of the following characteristics:

- lack of debris flow deposits along the channels or within the fan areas;
- lack of steep channel gradients;
- lack of high impact marks on trees along the channels; and
- the size of possible sideslope failures which are considered too small to trigger debris flows.

Francis Creek is capable of producing debris flows because of steep headwater slopes, a sufficiently steep channel gradient, high discharge and significant sediment supply. Martin Creek is not considered to produce debris flows at the design event return period. However, a debris flow or debris flood on Francis Creek could partially overflow into the Martin Creek watershed.

This assessment focuses on debris floods for Panorama Creek, Mathews Creek, Gavles Creek, Cove Creek, and Cleopatra Creek, and debris flows for Martin Creek and Francis Creek. It is recognized, however, that debris flows may occur on the former creeks at less than the design event return period.

DEBRIS FLOW AND DEBRIS FLOOD INITIATION

Debris Floods on Deep Cove Creeks

Debris floods can be triggered by a variety of processes, but for the study area the most likely mechanisms are:

- a small sideslope failure occurring during a major rainstorm that temporarily blocks the creek and causes an outbreak flood as the landslide dam is breached;

- a small sideslope failure occurring during a major rainstorm that reaches the main channel causing much of the material to become entrained and transformed into a debris flood; and

- a log jam breach mobilizes the loose sediment and organic debris stored in an upstream sediment wedge, and the mobilized saturated debris then entrains additional channel debris.

In all three scenarios, a substantial amount of debris would be mobilized, and although some of it would be deposited along the channel before reaching the fan, much of it may be delivered into the area of development. This occurrence may cause injuries and significant property damage.

It is important to note that a debris flood in any of the Deep Cove creeks is most likely to initiate in the gullied reaches between Indian River Drive and Panorama Drive (below the benchlands. The channel gradients are sufficiently steep and there is significant debris within the channels for such occurrences. Due to the confined nature of the gullies, a flood surge from a channel blockage would remain in the channel and travel to the developed areas. Undersized culverts and creek cross-sections could overflow at a number of locations.

Debris floods are unlikely to occur further upslope due to significantly less sediment storage and a general lack of confinement (i.e. no long and steep sideslopes for debris slides to initiate on). While a small debris flood could potentially initiate between Mount Seymour Road and Indian River Drive, its momentum would rapidly dissipate upon reaching the relatively small culverts along Indian River Drive.

Debris Flows on Francis Creek and Martin Creek

The same processes as described above could initiate debris flows at Francis Creek. However, the most likely scenario is a debris slide impacting the main channel in the area upstream of the upper switchback on Mount Seymour Road. For a debris slide to be effective, it would have to reach the channel at an oblique angle and thereby transfer its momentum to the channel. Debris slides capable of triggering debris flows are most likely to occur on the left (east) side of Francis Creek where the sideslopes are steep and up to 60 m in length. Potential debris flows could impact areas either upstream or downstream of the waterfall on Francis Creek (Figure 2-1).

Debris flows could also be initiated by log jams or landslide dams blocking the channel. The most likely location for a channel blockage is at the upper switchback of Mount Seymour Road where part of the road fill is being undercut by the creek.

Debris flows on Francis Creek could partially overflow into the Martin Creek watershed upstream of Indian River Drive (Figure 2-1). Such events would likely continue down Martin Creek to Deep Cove.

DEBRIS FLOW AND DEBRIS FLOOD PROBABILITY

Debris flow and debris flood hazards are defined by a combination of probability and magnitude. This sub-section determines the probability or frequency of debris flows and debris floods for the Deep Cove creeks. Debris flow and debris flood probabilities are defined as per Table E-1.

Table E-1: Debris Flow and Debris Flood Probabilities and their Significance

Relative Term of Probability	Return Period	Probability of at Least One Occurrence in 50 Years	Significance of Probability
Very High	less than 20 years	more than 90%	The hazard is imminent, and very likely to occur within the lifetime of a person or structure. There will generally be clear and relatively fresh signs of disturbance.
High	20 to 100 years	40% to 90%	The hazard is likely to happen within the lifetime of a person or structure. Disturbances are clearly identifiable from deposits and vegetation, but may not appear fresh.
Medium	100 to 500 years	10% to 40%	The hazard is possible within a given lifetime. Signs of disturbance such as vegetation damage may not be easily noted. A probability of 10% in 50 years is used by the BC Ministry of Transportation as a design standard for natural hazards.
Low	more than 500 years	less than 10%	The potential hazard is lower than the level normally considered for creek management purposes, but which may be worthy of consideration in long-term land use planning activities.

Dating Methods and Results

Three dating methods can be used to determine the frequency of past creek events: historic air photograph analysis, dendrochronology and documented events from newspapers and other reports.

A sequence of air photographs were inspected dating back to 1945. None of these photos showed evidence of debris flows on the fan or along the channel. No large sideslope failures were identified that would indicate a possible initiation of a debris flow. It should be noted that failures and debris flows would have to be large enough to snap trees to be clearly visible from air photos. Smaller events remain unnoticed due to a dense tree canopy. From this evidence, it is concluded that the Deep Cove creeks have not witnessed a debris flow or large debris flood for at least 55 years.

The second dating method is dendrochronology. Debris flows can impact trees and leave scars, which subsequently overgrow. Cutting a wedge from this scar tissue allows the reconstruction of the year of damage. In addition, if trees are partially covered with debris, growth often slows considerably. Coring a tree and counting back to a ring sequence that is very narrow enables a researcher to determine the date of the debris flow. No suitable trees were found for either dendrochronological method. On many of the creeks, there are trees up to approximately 70 years old adjacent to the channel. It is highly probable that any debris flow activity during the last 70 years would still be visible as an impact scar on some of the trees. However, the lack of datable scars suggests that no debris flow or large debris flood has occurred for at least 70 years on any of the creeks. Several trees were found to have minor scars near the root horizon, but it was inconclusive whether these scars were caused by normal flood flow or debris floods.

The third method is documented events from newspapers or other reports. No direct references to major events were found.

In summary, the available evidence suggests that neither debris flows nor large debris floods have occurred on any of the studied Deep Cove creeks for at least 70 years. Smaller debris floods have no doubt occurred, but cannot be dated because it is not possible to separate evidence of normal flood flow from debris floods.

DEBRIS FLOW MAGNITUDE AT FRANCIS CREEK AND MARTIN CREEK

Determination of debris flow magnitude involves consideration of both the total volume of a debris flow and the peak discharge. Total volume is important for those mitigative structures that contain the debris, whereas peak discharge estimates are required for mitigative structures that channelize the debris and for the design of creek crossings.

In this appendix, the design debris flow and debris flood is defined as having a return period of approximately 500 years, which corresponds roughly to a 10% probability of occurrence in 50 years. This probability is used by the Ministry of Transportation as a design criterion for hazard analysis (mostly rockfall). The upper limit of the medium probability scenario in Table E-1 reflects this probability.

Design Debris Flow Volume at Francis Creek and Martin Creek

For Francis Creek, the medium probability debris flow event is postulated as follows:

- a large debris slide in the upper watershed or a channel blockage initiates a debris flow;
- due to a stepped channel profile, intermittent deposition occurs;
- partial avulsion into the drainage of Martin Creek occurs at an elevation of approximately 280 m;
- additional material is stored above Indian River Drive where a small debris basin has been excavated; and
- the remaining material travels to the Deep Cove Marina at Indian Arm.

The corresponding debris flow volume is calculated according to the following equation:

$$V_{total} = V_{storage\ volume} + V_{point\ source} - V_{avulsion} - V_{deposited} - V_{debris\ basin}$$

The debris storage volume calculation is summarized in Table E-2.

For bedrock channels like Francis Creek, the storage volume can be determined by estimating the amount of debris that is overlying the bedrock for a given reach. Based on a traverse of Francis Creek, debris storage volumes were estimated and are summarized in Table E-2. The upper limit of debris flow initiation is located at an elevation of about 675 m.

Table E-2: Storage Volumes for Francis Creek

Elevation (m asl)	Slope (°)	Reach Length (m)	Storage Volume (m^3)
0 - 45	28	95	50
45 - 95	10	365	185
120 - 190	8	505	250
190 - 200	3	40	0
199 – 220	13	90	360
220 – 225	15	50	105
225 – 265	9	105	210
265 – 285	40	135	135
285 – 305	8	95	285
305 – 335	12	120	240
335 - 345	20	60	120
345 – 375	15	220	655
375 - 400	14	100	410
400 – 470	35	160	960
470 – 490	35	65	35
490 - 555	20	210	40
555 - 620	20	185	90
620 – 650	25	85	20
650 - 675	20	80	10
TOTAL			**4,000**

The above calculations suggest that approximately 4,000 m^3 of in-channel debris is available to be mobilized during a debris flow if initiated below 675 m elevation.

To calculate the debris flow volume, the total volume of debris stored in the channel is added to the largest conceivable point source failure. For Francis Creek, debris slides are unlikely to exceed 500 m^3, given the very shallow soil and the lack of steep long sideslopes. The amount of debris mobilized would then total 4,500 m^3.

The most conservative scenario assumes that a debris flow initiates upstream of the majority of channel debris. However, it is unlikely that this amount would reach the fan area (Deep Cove Marina parking lot). First, Francis Creek is poorly confined at an approximate elevation of 280 m and avulsion to the southwest is possible (Figure 2-1). As much as half of the mobilized volume upstream of 280 m elevation could avulse into the Martin Creek drainage (approximately 1,000 m^3). Second, some 500 m^3 of material could be stored upslope of Indian River Drive, where a small debris basin has been excavated. Finally, Francis Creek is characterized by a stepped profile with steep sections (> 20º) altering with flat sections (<10º). Intermittent deposition of debris flow material is likely along the flatter channel sections, which could total approximately 2,000 m^3. Hence, the volume of debris that could reach the fan area is estimated at 1,000 m^3.

The debris flow volume calculation is completed in Table E-3 for Francis Creek.

Table E-3: Estimation of Design Debris Flow Volume at Francis Creek

Component	Volume (m^3)
Point source from initiating failure	+ 500
Debris volume in storage	+ 4,000
Partial avulsion at 280 m elevation into Martin Creek drainage	-1,000
Material deposition due to stepped profile	- 2000
Storage above Indian River Drive	- 500
Total Debris Flow Volume at Indian Arm	1,000

Design Debris Flow Peak Discharge at Francis Creek and Martin Creek

The second step in assessing debris flow magnitude for Francis Creek is to estimate peak discharge. To estimate the peak discharge of bouldery debris flows in southwestern B.C., Jakob (1996) suggested the following equation:

$$\mathbf{Q_p = (V_{max}/28)^{0.9}} \qquad \text{(E-1)}$$

where Q_p is the mean discharge derived from a regression line, and V_{max} is the total volume of the debris flow.

Using Equation E-1, the peak discharge of Francis Creek at the fan is estimated at 25 m^3/s. A similar discharge is estimated for Martin Creek in the event of a 1,000 m^3 avulsion from Francis Creek. The estimated volume and peak discharge for Martin Creek is for a debris flow arriving at Indian River Drive. Here, the creek flows through a 600 mm wooden culvert within a well defined gully. Because the channel is well vegetated and a significant portion of the debris flow could remain in storage at the crossing, it is difficult to estimate the magnitude of the event for downstream reaches.

Given estimates of peak discharge, the existing channel can be evaluated to determine whether it is likely to be overtopped by a debris flow. Table E-4 summarizes channel cross-section information from four detailed sections measured downstream of 280 m elevation. Existing channel capacity is based on the cross-section area times velocity. While it is very difficult to predict debris flow velocities, several direct observations and back calculations for other events in the coastal mountains of B.C. have yielded estimates typically averaging 5 m/s.

Table E-4: Approximate Channel Cross-Sections at Selected Sites on Francis Creek

XS	Location	Area (m^2)	Velocity (m/s)	Capacity (m^3/s)	Peak Discharge of Design Debris Flow (m^3/s)
1	280 m elevation	2	5	10	70
2	225 m elevation	0.25	5	1.25	25
3	d/s Indian River Dr.	4	5	20	25
4	box culvert/marina	1	5	5	25

Table E-4 demonstrates the potential for channel avulsion at 280 m elevation and the inadequacy of the box culvert immediately upstream of the marina. In both cases, the design debris flow significantly exceeds channel capacity.

CREEK EVENT SCENARIOS AT FRANCIS CREEK AND MARTIN CREEK

Debris flow and debris flood scenarios have been postulated for the four probability categories. These scenarios, summarized in Table E-5, are based on the preceeding analysis, supplemented by local experience and professional judgement.

Table E-5: Scenarios for Different Event Probabilities at Francis Creek and Martin Creek

Process	Probability	Probability of at least one occurrence in 50 years	Estimated Debris Volume (m^3)	Estimated Peak Discharge (m^3/s)	Scenario
Flood	Very High	more than 90%	several tens	5	Heavy rainfall and/or rain-on-snow causes a flood mobilizing smaller boulders and some organic material (Francis Creek).
Debris Flood	High	40% to 90%	up to 500	up to 15	During heavy rainfall and/or rain-on-snow, a log jam or landslide dam may breach causing a large floodwave to travel downstream (Francis Creek).
Debris Flow	Medium	10% to 40%	up to 1,000	up to 25	A logjam or landslide dam breach or debris slide on Francis Creek causes sudden debris mobilization. A debris flow ensues. Some material is deposited along the channel, while up to 1,000 m^3 avulses at 280 m elevation into the Martin Creek watershed. Debris is stored intermittently along the channel and upstream of Indian River Drive. Approximately 1,000 m^3 may reach the fan area, where the box culvert is plugged and debris spills out over the Marina parking lot.

Process	Probability	Probability of at least one occurrence in 50 years	Estimated Debris Volume (m^3)	Estimated Peak Discharge (m^3/s)	Scenario
Debris Flow	Low	less than 10%	up to 2,000	up to 45	As above, but in this case material does not avulse into the Martin Creek watershed and 2,000 m^3 reaches the Marina. (For Martin Creek, the low probability scenario is for an avulsion of 1,500 m^3 from Francis Creek.)
Volume and peak discharge estimates represent the upper end of return periods.					

OTHER DEEP COVE CREEKS

For the other Deep Cove creeks (Panorama Creek to Cleopatra Creek), the medium probability debris flood is postulated as follows:

- a sideslope failure downslope of Indian River Drive is transformed into a debris flood or causes a channel blockage;
- the debris flood mobilizes additional material down to Panorama Drive; and
- channel avulsion occurs due to undersized culverts or insufficient cross-sectional area.

Unlike debris flows, there are no reliable methods available to estimate either the peak discharge or total volume of debris floods. In light of this, debris flood peak discharges were estimated using work done by Jakob and Jordan (2001) who showed that the peak discharge of 500-year return period debris floods can be two to five times the 200-year return period flood. In this study, a factor of two to three was chosen for the 500-year return period debris floods. A lower range was chosen given the relatively small size of the watersheds (a factor of 3 was chosen for the more active watersheds). The associated debris flood volumes are based on geomorphic judgement following a traverse of each of the creeks from Deep Cove to about 500 m elevation.

Debris flow, debris flood, and flood scenarios for the various event probabilities are summarized in Table E-6 for Panorama Creek, Mathews Creek, Cove Creek, Gavles Creek and Cleopatra Creek. Because of similar channel and geomorphic characteristics, they have not been separated into individual tables.

Table E-6: Scenarios for Different Event Probabilities at Panorama, Mathews, Cove, Gavles and Cleopatra Creeks

Process	Probability	Probability of at least one occurrence in 50 years	Estimated Debris Volume (m^3)	Estimated Peak Discharge (m^3/s)	Scenario
Flood	Very High	more than 90%	up to 5	up to 3	Heavy rainfall and/or rain-on-snow causes a flood mobilizing smaller boulders and some organic material. Some debris may spill into residents' back yards.
Debris Flood	High	40% to 90%	up to 20	up to 6	A small sideslope failure causes a surge in sediment movement, which will dilute into a debris flood. Branches and smaller root wads may be transported. Some debris is likely to spill out of the channels.
Debris Flood	Medium	10% to 40%	up to 250	up to 10	A sideslope failure causes a surge in sediment movement, which dilutes into a debris flood. Branches and root wads may be transported. Some debris is likely to spill out of the channels. Damage may occur to structures along Panorama Drive.
Debris Flow	Low	less than 10%	up to 800	up to 20	A large (>100 m^3) sideslope failure transfers into a debris flow at impact with the channel. Most channel debris will be entrained and sideslopes undercut. Significant damage will occur to structures along Panorama Drive.
Volume and peak discharge estimates represent the upper end of return periods.					

The associated event magnitudes for these creeks are summarized in Table E-7.

Table E-7: Design Event Magnitude for Deep Cove Creeks

Probability	Volume (m^3)	Peak Discharge (m^3/s)	Geomorphic Process
Panorama Creek			
Very High	5	3	flood
High	20	6	debris flood
Medium	200	10	debris flood
Low	600	16	debris flow
Mathews Creek			
Very High	5	3	flood
High	15	5	debris flood
Medium	150	9	debris flood
Low	500	13	debris flow
Gavles Creek			
Very High	5	2	flood
High	20	4	debris flood
Medium	250	8	debris flood
Low	800	20	debris flow
Cove Creek			
Very High	5	3	flood
High	20	6	debris flood
Medium	250	10	debris flood
Low	800	20	debris flow
Cleopatra Creek			
Very High	2	1	flood
High	10	2	debris flood
Medium	100	4	debris flood
Low	400	11	debris flow

SUMMARY

This appendix documents the debris flow and debris flood hazard at the Deep Cove creeks, by determining the frequency and magnitude of events. It was not possible to reconstruct a frequency of debris floods and debris flows because none of the absolute dating methods used or considered were applicable. However, at least 70 years have passed in the Deep Cove creeks without a significant debris flow or debris flood occurrence.

The design debris flood volume for the Deep Cove creeks except Martin and Francis Creeks, which corresponds to a 500-year event (medium probability class), is estimated to range between **100 and 250 m^3**. The associated peak discharge is estimated to range between **4 and 10 m^3/s**. Debris floods are most likely to initiate in the gullied reaches below 150 m elevation and impact developed areas along Panorama Drive. Debris floods

are unlikely to initiate further upslope due to significantly less sediment storage and a general lack of confinement.

Francis Creek is capable of producing debris flows because of steep headwater slopes, an overall steeper gradient, higher discharge and sediment wedges of significant size. The design debris flow event for Francis Creek has an estimated volume of **1,000 m^3** and a peak discharge of **25 m^3/s**. The estimated values are for a debris flow at the Deep Cove Marina.

As well as impacting the marina, a medium probability debris flow on Francis Creek could avulse into the drainage of Martin Creek at an elevation of 280 m. Here the creek is poorly defined and an incised channel toward the south is evidence of previous avulsions. The design debris flow magnitude for Martin Creek is estimated to **1,000 m^3** arriving at Indian River Drive with an associated peak discharge of **25 m^3/s**.